



CP 2-Cathodic Protection Technician Course Manual

April 2005
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Acknowledgements

The time and expertise of a many members of NACE International have gone into the development of this course. Their dedication and efforts are greatly appreciated by the authors of this course and by those who have assisted in making this work possible.

The scope, desired learning outcomes and performance criteria were prepared by the Cathodic Protection Training and Certification Program Task Group under the auspices of the NACE Certification and Education Committees. Special thanks go to the following:

On behalf of NACE, we would like to thank the following members who were instrumental in the development and review of this program.

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This group of NACE members worked closely with the contracted course developers, who were John Fitzgerald, John Wagner, and Walter Young of Corrpro Cos. Inc. Much of the material in the courses is based on existing NACE cathodic protection training material which was developed and refined over several years by members including Robert A. Gummow, (CorrEng, Downsview, Ontario), James R. Myers (JRM Associates, Franklin, Ohio), Frank Rizzo (FERA Corporation, Houston, Texas), Marilyn Lewis, P.E. (Lewis Engineering, Hattiesburg, MS), Larry Brandon (CorPre Tek, Inc., Hubbardston, MI) and James F. Jenkins, P.E. (Cambria, California).

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Glossary of Terms

“Factors Affecting the Accuracy of Reference Electrodes”, Frank Ansuini and James R. Dimond, Materials Performance, November, 1994 (NACE International, Houston, TX).

RP0169 “Control of External Corrosion on Underground or Submerged Metallic Piping Systems”

RP0285 “Corrosion Control of Underground Storage Tank Systems by Cathodic Protection”

RP0176 “Corrosion Control of Steel Fixed Offshore Platforms Associated with Petroleum Production”

RP0388 “Impressed Current Cathodic Protection of Internal Submerged Surfaces of Steel Water Storage Tanks”

RP0177 “Mitigation of Alternating Current and Lightning Effects on Metallic Structures and Corrosion Control Systems”

RP0575 “Internal Cathodic Protection Systems in Oil Treating Vessels”

RP0193 “External Cathodic Protection of On-Grade Metallic Storage Tank Bottoms”

RP0196 “Galvanic Anode Cathodic Protection of Internal Submerged Surfaces of Steel Water Storage Tanks”

RP0290 “Cathodic Protection of Reinforcing Steel in Atmospherically Exposed Structures”

RP0200 “Steel Cased Pipeline Practices”

TM0497 “Measurement Techniques Related to Criteria for Cathodic Protection on Underground or Submerged Metallic Piping Systems”

TM00101 “Measurement Techniques Related to Criteria for Cathodic Protection on Underground or Submerged Metallic Storage Tanks”

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NACE strives to mail out student examination results within 14 working days after the conclusion of each course. Examination results are not available via telephone.

Information regarding the current status of grade letters for your course will be available on the NACE website within **10 working days** after the course ends. When the letters for your course are mailed, the report will show a mail date in the status column.

Just go to <http://nace.org/NACE/Content/Education/GradeStatus.asp> or visit the NACE Website at www.nace.org and click on Education/Certification tab then click on Grade Status.

All you need to find your course information is the following:

Course Name
Course Location
Course Date

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Carol Steele
E-Mail: carol.steele@mail.nace.org
Phone: 281/228-6244
Fax: 281/228-6344

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NACE is now making grades available on the Internet. If you want to participate, please insert your student ID# AND a 4-digit password on your examination ParScore sheet (see example).

- ◆ Your student ID is listed on your registration confirmation notice.
- ◆ Create your own 4-digit password (*the password you choose should be written in the phone number box*).

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ParSCORE™
STUDENT ENROLLMENT SHEET
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then click on Education/Certification

then click on Student Grades

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NUMBER** _____

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NUMBER** _____

PASSWORD _____
(Only Four Digits)

**Keep this in
a safe place**

NACE CORROSION NETWORK (NCN)

NACE has established the NACE Corrosion Network, an electronic list serve that is free to the public. It facilitates communications among professionals who work in all facets of corrosion prevention and control.

If you subscribe to the NACE Corrosion Network, you will be part of an E-mail-driven open discussion forum on topics A-Z in the corrosion industry. Got a question? Just ask. Got the answer? Share it! The discussions sometimes will be one-time questions, and sometimes there will be debates.

The topics will range from questions and answers about cathodic protection to materials and chemical inhibitors and tons more!

What do you need to join? An E-mail address. That's all! Then:

1. Send a blank email message to:
Join-nace@nacecorrosionnetwork.com
2. To Unsubscribe, send a blank e-mail to:
Leave-nace@nacecorrosionnetwork.com
3. You're done! You'll get an e-mail back telling you how to participate, but it's so easy that you'll figure it out without any help.

CP 2–Cathodic Protection Technician Course Outline

DAY ONE	
	Introduction, Welcome, Overview
Chapter 1	Corrosion Theory
DAY TWO	
Chapter 2	Cathodic Protection Fundamentals
Chapter 3	Cathodic Protection Systems
Chapter 4	DC Power Sources for Cathodic Protection
DAY THREE	
Chapter 4	DC Power Sources for Cathodic Protection (continued)
Chapter 5	Safety
Chapter 6	Field Measurements
	Introduction to Indoor Field Measurement Test Stations
	Indoor Field Measurement Test Station Practice
DAY FOUR	
	Outdoor Field Program (weather permitting)
Chapter 7	Stray Current and CP Interference
	Indoor Field Measurement Test Stations
DAY FIVE	
Chapter 8	Monitoring and Records
	Timed Practice with Indoor Field Measurement Test Stations
	Course Review
DAY SIX	
	Written and Practical Examinations

The Course

Corrosion is one of the most important problems encountered by the owners and operators of underground, offshore, submerged and other metallic structures exposed to an electrolyte. If corrosion is not controlled, it can lead to large costs in repairs or facility replacement. Even greater costs can be incurred from environmental damage, injuries and fatalities.

Corrosion control personnel must have a good basic understanding of corrosion mechanisms. They also need to know the various conditions under which corrosion can occur on underground facilities.

The CP 2–Cathodic Protection Technician training course is the second course in the 4-level NACE Cathodic Protection Training and Certification Program. This course will focus of the topics of corrosion theory, cathodic protection principles and systems, advanced field testing and data collection.

Audience (Who Should Attend)

This course is designed for persons who either have a heavy engineering/scientific background and some working knowledge of cathodic protection, or who have extensive years of field experience with some technical background.

Prerequisites

To attend this training course, students must meet the following prerequisites:

Path 1:

- 3 years cathodic protection work experience
- High School diploma or GED
- CP 1–Cathodic Protection Tester certification or equivalent training

Path 2:

- 1 year cathodic protection work experience
- 4-year Physical Science or Engineering degree
- CP 1–Cathodic Protection Tester certification or equivalent training

Path 3:

- 2-year post high-school training from an approved Math or Science Technical or Trade School
- 2 years cathodic protection work experience
- CP 1–Cathodic Protection Tester certification or equivalent training

Length

The course will begin on Sunday at 1:00 pm and concludes on Friday at 5 pm.

Reference Books

Students have the option of selecting one of the following reference books: *Peabody's Control of Pipeline Corrosion, Second Edition* or *Pipeline Corrosion and Cathodic Protection, Third Edition*.

Experiments

Throughout the week there will be in-class experiments to help demonstrate and reinforce principles discussed in the lecture sections.

CAUTION: Students should realize that these experiments are conducted under controlled conditions, field conditions will vary.

Field Training

Students will participate in a field training activity at a training site, weather permitting. The field training activity is designed to simulate actual field conditions that students may encounter on-the-job. Students will perform tests and collect data.

Tests and Quizzes

Chapter quizzes will be distributed to students during the week and reviewed in class by the instructors.

The CP 2–Cathodic Protection Technician course has both written and practical (hands-on) final examinations. The final examinations will be given on Friday.

The final written examination consists of 100 multiple-choice questions. The written final examination is open book and students may bring reference materials and notes into the examination room.

The final practical examination is closed book.

A score of 70% or greater on both the written and practical examination(s) is required for successful completion of the course and to obtain certification. All questions are from the concepts presented in this training manual.

Non-communicating, battery-operated, silent, non-printing calculators, including calculators with alphanumeric keypads, are permitted for use during the examination. Calculating and computing devices having a QWERTY keypad arrangement similar to a typewriter or keyboard are not permitted. Such devices include but are not limited to palmtop, laptop, handheld, and desktop computers, calculators, databanks, data collectors, and organizers. Also excluded for use during the examination are communication devices such as pagers and cell phones along with cameras and recorders.

Certification Application

Successful completion of both the written and practical examination and approval of the CP 2–Cathodic Protection Technician certification application is *required* before certification will be issued.

Cathodic Protection Certification Application

CP 2 - Cathodic Protection Technician

(Must be submitted to NACE Headquarters 60 days prior to course attendance)

Please Note – This Is **Not** A Class Or Exam Registration

Please Contact NACE Registrar (281/228-6223) For Class or Exam Registration

NACE Member: ☐ Yes ☐ No Member # _____

Applicant's Name: _____

Home Address: _____

Company Name: _____

Company Address: _____

Country: _____ Zip/Postal Code: _____

Phone: Home _____ Business _____ Fax _____

E-mail: _____

PRINTED NAME: _____

I affirm that:

1. I understand that I am **solely** responsible for making sure that all necessary work experience documentation is complete and submitted in good order to NACE Headquarters.
2. I understand that if I knowingly provide, or cause to be provided, any false information in connection with my recognition under the NACE International Training and Certification Program, that it will be grounds for action against my standing in the program.
3. I understand that the names of the categories within the NACE International Cathodic Protection Training and Certification Program are as follows:

Highest Program Step Successfully Completed	Category Name
CP 1	Cathodic Protection Tester
CP 2	Cathodic Protection Technician
CP 3	Cathodic Protection Technologist
CP 4	Cathodic Protection Specialist

4. I understand that the registration number and/or category title may be used **only by Certified Cathodic Protection persons** (persons who have successfully completed CP1, CP 2, CP 3 or CP 4). I understand that this applies to business cards, stationery, advertisements, etc. I understand that in no case may the NACE International logo, NACE International Cathodic Protection logo, or other NACE insignia be used. I understand that violation of these rules will result in action against my standing in the program on the basis of violation of the NACE International Cathodic Protection Program Attestation.
5. I (re)affirm the NACE International Cathodic Protection Certification Program attestation, reproduced on the back side of this sheet, and agree to abide by its provisions as long as I hold any level of recognition under the program.

Signed: _____

Date: _____

**THIS DOCUMENT MUST BE SIGNED AND RETURNED WITH APPLICATION
RETAIN A COPY OF THIS DOCUMENT FOR YOUR RECORDS**

NAME: _____

PLEASE CHECK APPROPRIATE BOX (choose only one):

☐

I AM APPLYING FOR CP 2 **CLASS & EXAM** SCHEDULED FOR:

(Please list city/dates of course you are planning to attend) _____



Click here for COURSE SCHEDULE

OR

☐

I AM APPLYING FOR CP 2 **EXAM ONLY** SCHEDULED FOR:

(Please list city and date of exam you are planning to attend) _____



Click here for EXAM ONLY SCHEDULE

REQUIREMENTS FOR Cathodic Protection Technician

Please provide the necessary **cathodic protection** work experience in accordance with the following requirements for acceptance in class or exam checked. Cathodic protection is defined as a technique to reduce the corrosion of a metal surface by making that surface the cathode of an electrochemical cell.

CP 2 CLASS & EXAM

3 years **cathodic protection** work experience **REQUIRED**

PLUS

High school diploma or GED **REQUIRED**

CP 1 Certification or equivalent training **REQUIRED**

OR

1 year of **cathodic protection** work experience **REQUIRED**

PLUS

4-year Physical Science or Engineering Degree **REQUIRED**

PLUS

CP 1 Certification or equivalent training **REQUIRED**

OR

2 years **cathodic protection** work experience **REQUIRED**

PLUS

2-year post-high school training from approved Math or Science Technical/Trade School **REQUIRED**

PLUS

CP 1 Certification or equivalent training **REQUIRED**

CP 2 EXAM ONLY

3 years **cathodic protection** work experience **REQUIRED**

PLUS

High school diploma or GED **REQUIRED**

CP 2 class **or** equivalent training **RECOMMENDED**

OR

1 year of **cathodic protection** work experience **REQUIRED**

PLUS

4-year Physical Science or Engineering Degree **REQUIRED**

PLUS

CP 2 class **OR** equivalent training **RECOMMENDED**

OR

2 years **cathodic protection** work experience **REQUIRED**

PLUS

2-year post-high school training from approved Math or Science Technical/Trade School **REQUIRED**

PLUS

CP 2 class **or** equivalent training **RECOMMENDED**

Please provide the necessary **cathodic protection** work experience in accordance with above requirements for acceptance in class or exam checked.

G/cd/cp-cert/cp cert II application forms

S A M P L E

Form 1: Summary of **Cathodic Protection** Related Work Experience

Instructions: Make and use as many copies of this form as needed. Please provide all information requested. Forms must be printed legibly in black ink or typed. Illegible information can delay the application process. For assistance with this form, contact the Education Division at NACE International Headquarters.

Applicant Information:

Name: A. Sample Phone: 409/111-4321

Company: ZZZ Coating Inspection Inc. Fax: 409/111-1234

Address: 987 Gage Avenue

City: Millspec State/Province: TX

Zip/Postal Code: 77987 Country: USA

Please summarize below the information on each copy of Form 2, Individual Job Documentation. List your experience beginning with the most recent, followed by less recent experience.

From Month/Year	To Month/Year	Number of Months in this job	Job Title	Company Name
1/92	1/95	36	CP pipeline readings	ZZZ Gas Co.
12/89	12/91	24	Installer	AAA Tank Installers
12/87	12/89	24	Design Manager	ABC CP Design
/	/			
/	/			
/	/			
/	/			
/	/			
/	/			
/	/			

Applicant Affidavit: I understand that if I knowingly provide false information in connection with my recognition under this program, it will be grounds for disciplinary procedures.

Signed: _____

Date: _____

Form 1: Summary of **Cathodic Protection** Related Work Experience

Instructions: Make and use as many copies of this form as needed. Please provide all information requested. Forms must be printed legibly in black ink or typed. Illegible information can delay the application process. For assistance with this form, contact the Education Division at NACE International Headquarters.

Applicant Information:

Name: _____ Phone: _____

Company: _____ Fax: _____

Address: _____

City: _____ State/Province: _____

Zip/Postal Code: _____ Country: _____

Please summarize below the information on each copy of Form 2, Individual Job Documentation. List your experience beginning with the most recent, followed by less recent experience.

From Month/Year	To Month/Year	Number of months in this job	Job Title	Company Name
/	/			
/	/			
/	/			
/	/			
/	/			
/	/			
/	/			
/	/			
/	/			
/	/			

Applicant Affidavit: I understand that if I knowingly provide false information in connection with my recognition under this program, it will be grounds for disciplinary procedures.

Signed: _____ Date: _____

MAKE A COPY OF ALL PAGES OF THIS APPLICATION FOR YOUR RECORDS

Page ____ of ____

Job Information

E-mail: _____

Page ____ of ____

THIS SECTION MUST BE COMPLETED
Your application will be returned if this space is left blank

[illegible]

Signed: _____ Date: _____

Education and Training

NAME: _____

Please check applicable statement of qualification:

☐ 3 years **cathodic protection** work experience as documented in this application and hold a high school diploma or GED.

PLUS

CP Tester Certification or equivalent training as listed below (exam and course only) OR

CP Technician class or equivalent training as listed below (exam only)

OR

☐ 1 year **cathodic protection** work experience as documented on this application and a 4-year Physical Science or Engineering Degree (please complete information below and attach a copy of your degree)

PLUS

CP Tester Certification or equivalent training as listed below (exam and course only) OR

CP Technician class or equivalent training as listed below (exam only)

OR

☐ 2 years **cathodic protection** work experience as documented in this application and 2-year post high school training from approved Math or Science Technical/Trade School (please complete information below and attach copy of your diploma/certificate).

PLUS

CP Tester Certification or equivalent training as listed below (exam and course only) OR

CP Technician class or equivalent training as listed below (exam only)

EQUIVALENT TRAINING OR TRADE/TECHNICAL SCHOOL INFORMATION

Please list equivalent training OR trade/technical trade school information by providing name of school, course or training, company providing training, date of training, etc.

DEGREE INFORMATION

Name of College or University

Degree Received

Date Awarded

Student ID Number

B. ATTESTATION

I hereby:

- (1) Recognize and acknowledge that the proper control of cathodic protection can be critical to the safety and welfare of the general public and industrial facilities.
- (2) Recognize and acknowledge that the control of cathodic protection is obligatory to maximize conservation of our material resources, to reduce economic losses, and to protect the environment.
- (3) Recognize and acknowledge that the entire field of cathodic protection and its control encompasses the application of the knowledge and experience of many diverse disciplines and levels of technical competence which must often be consulted.
- (4) Recognize and acknowledge that only through continual association and cooperation with others in this field can the safest and most economical solutions be found to the many cathodic protection problems.
- (5) Recognize and acknowledge that the quality of my work reflects on the entire profession of corrosion control.

For these reasons I:

- (1) Agree to give first consideration in my cathodic protection work to public safety and welfare and to protection of the environment.
- (2) Agree to apply myself with diligence and responsibility to the cathodic protection work that lies within my area of competence.
- (3) Agree to pursue my work with fairness, honesty, integrity and courtesy, ever mindful of the best interests of the public, my employer, and of fellow workers.
- (4) Agree to not represent myself to be proficient or make recommendations in phases of cathodic protection work in which I am not qualified by knowledge and experience.
- (5) Agree to avoid and discourage untrue, sensational, exaggerated, and/or unwarranted statements regarding my work in oral presentations, written text, and/or advertising media.
- (6) Agree to treat as confidential my knowledge of the business affairs and/or technical process of clients, employers, or customers when their interests so require.
- (7) Agree to inform clients or employers of any business affiliations, interests, and/or connections which might influence my judgment.
- (8) Agree to uphold, foster and contribute to the achievement of the objectives of NACE International.

I understand that my failure to comply with these requirements could result in disciplinary action.

Signature: _____

Printed Name: _____

Date: _____

D. QUALIFICATION REFERENCE

APPLICANT: Complete Items D.1, D.2, and D.3 then forward this form to the person you have listed in Item D.3. Ask this person to complete the remainder of the form and return it directly to NACE International.

Qualification references may be submitted by the following, who have expertise in the **CATHODIC PROTECTION** field:

- Registered or chartered engineers
- Present and/or previous supervisor(s) of the applicant
- Present and/or previous professors/instructors of the applicant
- NACE International certificate holders. (For Corrosion Specialist and Specialty Area applicants, one Qualification Reference must hold a NACE Certificate at the level being applied for or higher, a P.E. registration, ICorr Professional Member or international equivalent.)

D.1 Applicant's full name: _____

D.2 Certification category applied for: _____

D.3 Name, title, address, and phone # of person who is familiar with the work experience of the applicant:

_____ Phone: _____

REFERENCE: The applicant is applying for CATHODIC PROTECTION recognition by NACE International. Applicants for certification must meet specific requirements; please see the list of these requirements on the following page. Evaluation of an applicant's qualifications also depends on assessment of professional CATHODIC PROTECTION experience by references. It is requested that you complete Items D.4 through D.13 on this form and return it directly to NACE.

D.4 I hold NACE Certification as a :

_____ Certified _____ No. _____

_____ I am a Registered engineer (or equivalent) _____

_____ State/Province: _____ Branch: _____ No: _____

Leave space blank if this section is not applicable

D.5 I have known the applicant for _____ years. What is/was the nature of the association?

Current Supervisor	_____	Previous Supervisor	_____
Current Client	_____	Previous Client	_____
Current Co-worker	_____	Previous Co-worker	_____
Current Professor/Instructor	_____	Previous Professor/Instructor	_____
Other	_____		

D.6 From personal knowledge, my assessment of the applicant's character and personal reputation is that it is

Excellent ☐ Average ☐ Below average ☐

D.7 From personal knowledge, I know that the applicant has been engaged in cathodic protection work for _____ years. (**"cathodic protection" is defined as a technique to reduce the corrosion of a metal surface by making that surface the cathode of an electrochemical cell.**)

D.8 Based on this personal knowledge, I know that the quality of the applicant's work in the field of **CATHODIC PROTECTION** is
Excellent ☐ Average ☐ Below average ☐

D.9 The applicant is proficient in the following phases of **CATHODIC PROTECTION**:

D.10 Would you employ, or recommend the employment of, the applicant for employment in the phase of **CATHODIC PROTECTION** work you have described in Item D. 9?
Yes ☐ No ☐

D.11 Please describe any major projects/activities in which the applicant has been involved in the field of **CATHODIC PROTECTION** work. Describe only those where you had personal knowledge of the applicant's work. Please indicate the degree of responsibility exercised by the applicant, the complexity of the project/activity, the degree of knowledge/skill required, etc. (Attach a separate sheet)

D.12 Additional remarks or amplifying information:

D.13 My signature below indicates that I have personal knowledge and expertise in the **CATHODIC PROTECTION** field upon which to evaluate the applicant's professional capabilities.

Signature: _____ Date: _____

Printed Name: _____

Return completed form to: NACE International, Certification Department, Attn Carmen Wisdom, 1440 South Creek Drive, Houston, TX 77084-4906 USA

**CATHODIC PROTECTION TECHNICIAN
CERTIFICATION REQUIREMENTS**

3 years **cathodic protection** work experience
PLUS
High school diploma or GED
Level 1 CP Certification or equivalent training

OR

1 year of **cathodic protection** work experience
PLUS
4-year Physical Science or Engineering Degree
PLUS
Level 1 CP Certification or equivalent training

OR

2 years **cathodic protection** work experience
PLUS
2-year post-high school training from approved Math or
Science Technical/Trade School
PLUS
Level 1 CP Certification or equivalent training

E. QUALIFICATION REFERENCE

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Phone: _____

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_____ State/Province: _____ Branch: _____ No: _____

Leave space blank if this section is not applicable

D.5 I have known the applicant for _____ years. What is/was the nature of the association?

Current Supervisor _____

Previous Supervisor _____

Current Client _____

Previous Client _____

Current Co-worker _____

Previous Co-worker _____

Current Professor/Instructor _____

Previous Professor/Instructor _____

Other _____(Please specify)

D.6 From personal knowledge, my assessment of the applicant's character and personal reputation is that it is

Excellent ☐

Average ☐

Below average ☐

D.7 From personal knowledge, I know that the applicant has been engaged in cathodic protection work for _____ years. (**"cathodic protection" is defined as a technique to reduce the corrosion of a metal surface by making that surface the cathode of an electrochemical cell.**)

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CERTIFICATION REQUIREMENTS**

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PLUS
High school diploma or GED
Level 1 CP Certification or equivalent training

OR

1 year of **cathodic protection** work experience
PLUS
4-year Physical Science or Engineering Degree
PLUS
Level 1 CP Certification or equivalent training

OR

2 years **cathodic protection** work experience
PLUS
2-year post-high school training from approved Math or
Science Technical/Trade School
PLUS
Level 1 CP Certification or equivalent training

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Leave space blank if this section is not applicable

D.5 I have known the applicant for _____ years. What is/was the nature of the association?

Current Supervisor _____ Previous Supervisor _____

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Current Co-worker _____ Previous Co-worker _____

Current Professor/Instructor _____ Previous Professor/Instructor _____

Other _____ (Please specify)

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OR

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Level 1 CP Certification or equivalent training

OR

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2-year post-high school training from approved Math or
Science Technical/Trade School
PLUS
Level 1 CP Certification or equivalent training

G. QUALIFICATION REFERENCE

APPLICANT: Complete Items D.1, D.2, and D.3 then forward this form to the person you have listed in Item D.3. Ask this person to complete the remainder of the form and return it directly to NACE International.

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_____ I am a Registered engineer (or equivalent) _____

_____ State/Province: _____ Branch: _____ No: _____

Leave space blank if this section is not applicable

D.5 I have known the applicant for _____ years. What is/was the nature of the association?

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Current Client	_____	Previous Client	_____
Current Co-worker	_____	Previous Co-worker	_____
Current Professor/Instructor	_____	Previous Professor/Instructor	_____
Other	_____(Please specify)		

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Excellent ☐ Average ☐ Below average ☐

D.7 From personal knowledge, I know that the applicant has been engaged in cathodic protection work for _____ years. (**"cathodic protection" is defined as a technique to reduce the corrosion of a metal surface by making that surface the cathode of an electrochemical cell.**)

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CERTIFICATION REQUIREMENTS**

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PLUS
High school diploma or GED
Level 1 CP Certification or equivalent training

OR

1 year of **cathodic protection** work experience
PLUS
4-year Physical Science or Engineering Degree
PLUS
Level 1 CP Certification or equivalent training

OR

2 years **cathodic protection** work experience
PLUS
2-year post-high school training from approved Math or
Science Technical/Trade School
PLUS
Level 1 CP Certification or equivalent training

Qualification References

A qualification reference is a person who will vouch for your technical competence. Two Qualification References are required, four are recommended. You are asked to give the names of persons (unrelated to you and not more than one from your company) who have personal knowledge of your cathodic protection experience and abilities or of your teaching in a cathodic protection-related field. Acceptable references are registered engineers, present supervisor, present clients, previous supervisors, previous clients, professors and instructors, and NACE International Certificate holders of at least the same category for which you are applying.

NOTE: You are to send these individuals a Qualification Reference form (Item D), which they must complete and return directly to NACE International. This is your responsibility. You should follow up with these people to ensure that they correctly complete and return the Qualification Reference forms in a timely manner.

Name #1 _____
Name #2 _____
Name #3 _____
Name #4 _____

(Optional)

Please describe below any information which you wish to be considered by the Application Review Board (such as, but not limited to: education [college, trade school], publications on corrosion subjects, other technical papers or books that you have authored or co-authored, any patents you have obtained as a direct result of your efforts, etc.). You may attach a maximum of two, single sided pages of additional information if you desire. Attachments of more than two single-sided pages will not be reviewed.

The Corrosion Cell

Corrosion is an electrochemical process involving the flow of electrons and ions. Metal loss (corrosion) occurs at the anode. No metal loss occurs at the cathode (the cathode is protected). Electrochemical corrosion involves the transfer of electrons across metal/electrolyte interfaces. Corrosion occurs within a corrosion cell which consists of four parts:

- Anode
- Cathode
- Electrolyte
- Metallic Path

The electrons generated by the formation of metallic ions at the anode pass through the electronic path to the surface of the cathodic areas immersed in the electrolyte. They restore the electrical balance of the system by reacting with positive ions in the electrolyte.

Referring to Figure 1.1, let us examine the process of corrosion for a single corrosion cell consisting of a single anode and a single cathode existing on the same metallic surface in water. The metal provides the anode, cathode, and electronic path of the corrosion cell. The water provides the electrolyte to complete the corrosion cell. The electrolyte has ionized so that hydrogen (H^+) and hydroxyl (OH^-) ions are present in small amounts (10^{-7}).

Metal ions leave the anodic surface going into the electrolyte, leaving behind electrons, which flow in the metallic path to the cathodic surface. At the cathodic surface, the electrons from the anode meet hydrogen ions from the solution. One hydrogen ion accepts one electron and is converted into a hydrogen atom. The hydrogen atom may combine with another hydrogen atom to form a molecule of hydrogen gas, which may either cling to the cathodic surface or be released as a bubble. In some cases, the hydrogen atom may enter the metal lattice and lead to hydrogen embrittlement (to be discussed under “Environmental Cracking”).

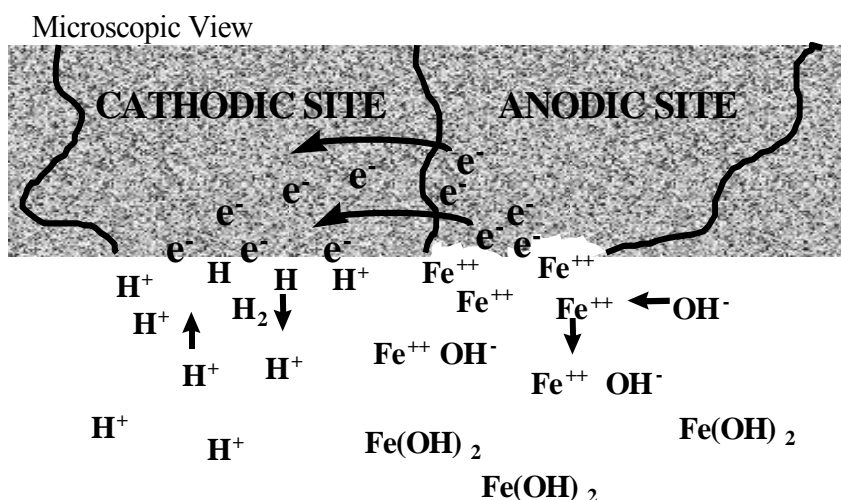


Figure 1.1 A Single Microscopic Corrosion Cell

Meanwhile, the metal ions combine with hydroxyl ions in the electrolyte to form metal hydroxide, or rust, which precipitates onto the metal surface.

As this process continues, oxidation (corrosion) of the metal occurs at the anodic surfaces and reduction of hydrogen ions occurs at the cathodes.

The graphite-zinc dry cell battery, as shown in Figure 1.2, often is used to illustrate the corrosion cell. As illustrated, zinc (anode) is electrically connected through an external load to carbon (cathode) in the presence of a corrosive electrolyte. When they are electrically connected, the corrosion cell is completed with the anodic reaction at the zinc and the cathodic reaction at the carbon electrode. The battery is depleted as the zinc is consumed.

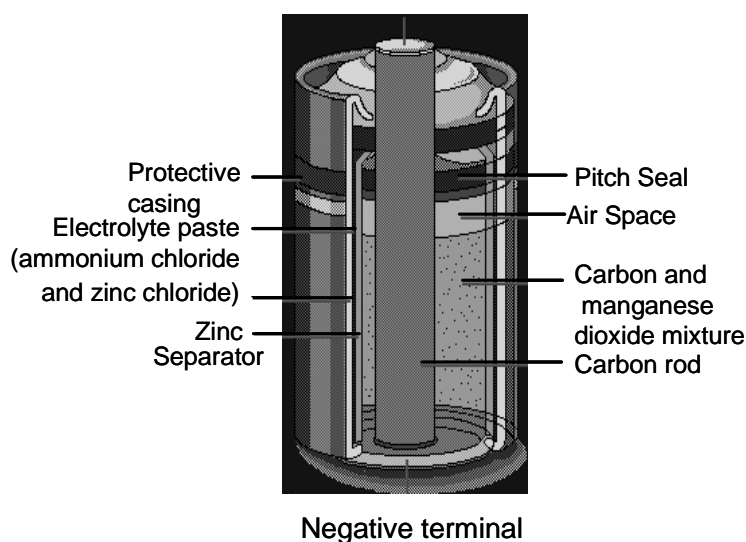


Figure 1.2 Graphite Zinc Battery

Remember: The term "oxidation" is not necessarily associated with oxygen.

Driving Force for Corrosion

Voltage

Corrosion involves a process in which electric charge flows from one metal surface, an anode, into the electrolyte and from the electrolyte onto a second metal surface, a cathode. The question now is "What causes the current to flow in the first place?"

Voltage is the measure of the electrochemical difference between two electrodes in an electrolyte. A metal immersed in an electrolyte will begin to corrode and exhibit what is known as an electrode potential. The electrode potential represents the reversible work to move a unit charge from the electrode surface through the solution to the reference electrode. It is equal to the potential difference between two points for which 1 coulomb of electricity will do 1 joule of work in going from one point to another. The electrode potential is measured against a standard reference cell.

Metal

The metal itself may be a source for the driving voltage of a corrosion cell. A difference in voltage may arise due to variations in: grain structure of a metal, composition formed during alloying, temperature or deformation of a single metal surface developed during fabrication.

Metals occur in nature in the form of various chemical compounds referred to as *ores*. After ore is mined, the metallic compound is removed from the rock-like ore and refined to produce a nearly pure state of the metal. Various processes—mechanical, chemical, and electrical—are employed to transform ores into useful metals. Regardless of the process, the metal absorbs energy during the transformation. The amount of energy required by a metal during the refining process determines the voltage or active state of the metal. The voltage is relatively high for such metals as magnesium, aluminum, and iron, and relatively low for such metals as copper and silver. The higher the energy, the more active the metal and the more tendency it has to corrode.

A typical cycle is illustrated by iron. The most common iron ore, hematite, is an oxide of iron (Fe_2O_3). The most common product of the corrosion of iron, rust, has the same chemical composition. The energy required to convert iron ore to metallic iron is "returned" when the iron corrodes to form the oxide.

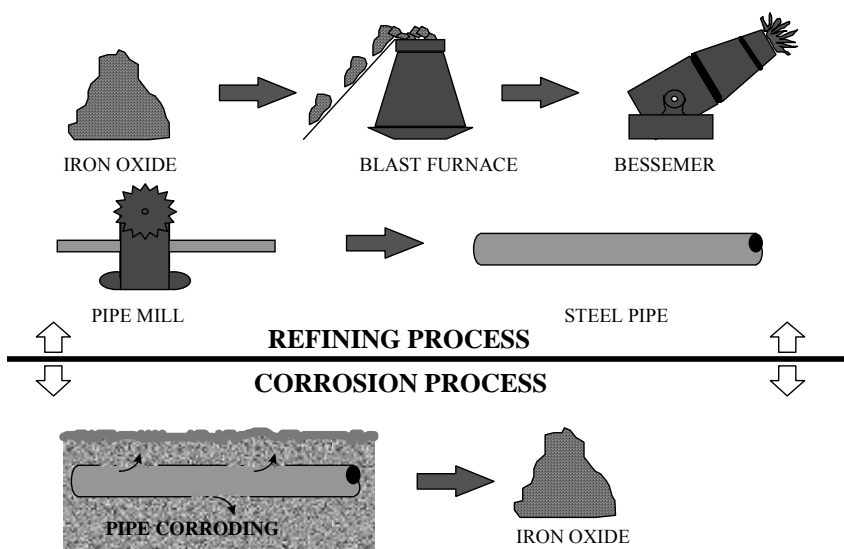


Figure 1.3 Refining Process of Steel

Figure 1.3 illustrates the refining and corrosion processes for iron and steel. Iron always is found in an oxidized state. It is mined from the ground as an ore. Energy is used to convert this iron oxide into iron and steel. It is loaded into a blast furnace where heat energy removes the oxygen and leaves elemental iron. It is then alloyed with other materials and loaded into a Bessemer furnace. Finally, it is rolled in a pipe mill, rod mill, etc., to form pipe, rebar, or structural shapes. When iron contacts an electrolyte, such as the earth or concrete, corrosion occurs. In the corrosion process, energy is lost and the iron combines with oxygen to form iron oxide. This corrosion product, rust, is identical to the iron oxide mined from the ground. Iron is considered thermodynamically unstable; given the right environment, iron will readily corrode to return to a lower energy state, such as rust.

Electromotive/Galvanic Series

The potential difference between metals exposed to solutions containing the respective ions at unit activity is represented in the standard emf series shown in Table 1.1. In this series, the metals are arranged from the most noble (e.g., gold) to the most active (e.g., magnesium).

Table 1.1 Partial Standard emf Series of Metals

Half-cell	Metal	Standard Electrode Potential E_o (volts) vs. SHE*
Au/Au ⁺⁺⁺	Gold	+1.498
Pt/Pt ⁺⁺	Platinum	+1.200
Cu/Cu ⁺⁺	Copper	+0.345
H ₂ /2H ⁺	Hydrogen	0.000
Pb/Pb ⁺⁺	Lead	-0.126
Ni/Ni ⁺⁺	Nickel	-0.250
Fe/Fe ⁺⁺	Iron	-0.440
Zn/Zn ⁺⁺	Zinc	-0.763
Al/Al ⁺⁺⁺	Aluminum	-1.662
Mg/Mg ⁺⁺	Magnesium	-2.363

*** Standard Hydrogen Electrode**

When two electrodes are placed in the electrolyte, electrochemical reactions will occur on each. If, for instance, one electrode is copper and the other is zinc, each will corrode and exhibit an electrode potential (as measured against a reference electrode). The potential between the two electrodes, also called the *electromotive force* (emf), is equal in sign and magnitude to the electrode potential of the anode less the electrode potential of the cathode. This emf or voltage between the two electrodes is the driving force for electrochemical corrosion. Note that the emf of a corrosion cell cannot necessarily be predicted from the standard emf series because (1) the emf series is produced under a standardized set of environmental conditions, and (2) metals polarize when connected together and this affects the voltage between them.

If a metallic path connects the two electrodes, the voltage difference will cause a current to flow between them (Figure 1.4). Current is the net transfer of electric charge per unit time.

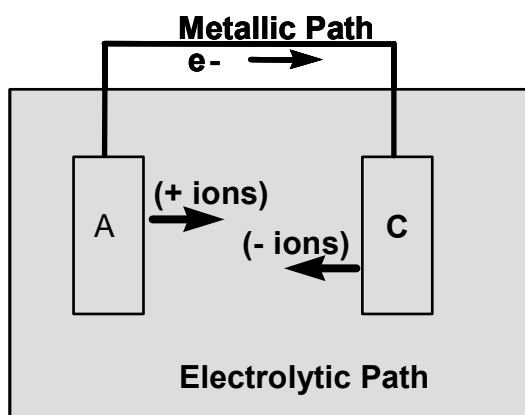


Figure 1.4 Charge Flow in an Electrochemical Corrosion Cell

When electrically interconnecting two different metals in a common electrolyte, the more active metal will tend to become the anode of the corrosion cell.

The standard emf series is a means of organizing metals in order of their tendency to corrode. The standard emf series has its limitations, as stated above. A more useful method of ordering metals is the galvanic series. A galvanic series is based on the behavior of a metal in a particular electrolyte and the most common electrolyte used is seawater. Table 1.2 lists a partial practical galvanic series in seawater.

Table 1.2 Practical Galvanic Series in Seawater

Metal	Volts vs. Cu-CuSO₄	Volts vs. Ag-AgCl
	Active or Anodic End	Active or Anodic End
Magnesium	-1.60 to -1.75	-1.55 to -1.70
Zinc	-1.10	-1.05
Aluminum	-1.05	-1.00
Clean Carbon Steel	-0.50 to -0.80	-0.45 to -0.75
Rusted Carbon Steel	-0.30 to -0.50	-0.25 to -0.45
Cast/Ductile Iron	-0.50	-0.45
Lead	-0.50	-0.45
Steel in Concrete	-0.20	-0.15
Copper	-0.20	-0.15
High Silicon Iron	-0.20	-0.15
Carbon, Graphite	+0.30	+0.35
	Noble or Cathodic End	Noble or Cathodic End

Nernst Equation

The Nernst Equation expresses the exact electromotive force of a cell in terms of the activities of products and reactants of the cell.

$$E = E^0 + \frac{RT}{nF} \ln \left(\frac{[a_M^{+ne}]}{[a_M]} \right) \quad \text{Eq. 1-1}$$

where:

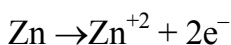
E^0	= Standard state half-cell electrode potential
E	= Electrode potential in existing solution
a_M^{+ne}	= Activity of metal ions in solution
a_M	= Activity of the metal ($a_M = 1$ for pure metal)
R	= Universal gas constant = 8.31431 joules, $^{\circ}\text{K}^{-1}$, mole $^{-1}$
T	= Absolute temperature (K) = 298.2 $^{\circ}\text{K}$
n	= Number of electrons transferred
F	= Faraday's constant (96,500 C/equivalent)

This equation shows that the metal ion concentration in the electrolyte affects the potential of the electrode. Potentials of metals listed in various publications are based on a stated set of conditions. Standard conditions for pure metals in the emf series are based on one unit activity of metal ions in the electrolyte at 25°C with no impurities in the metal or electrolyte and with reference to a standard hydrogen electrode.

The equation is often simplified by converting to logarithms to base 10 by multiplying by 2.303. Then the coefficient RT/F is often condensed to the value 0.0592 V, which is derived from $R=8.31431$ joules, $^{\circ}\text{K}^{-1}\cdot\text{mole}^{-1}$, $T=298.2$ $^{\circ}\text{K}$, $F=96,500$ C/equivalent. The Nernst Equation then becomes:

$$E = E_0 + \frac{0.059}{n} \times \log \left(\frac{a_M^{+ne}}{a_M} \right) \quad \text{Eq. 1-2}$$

As an example, we will calculate the potential of zinc in a 0.01 molar zinc chloride solution at 25 $^{\circ}\text{C}$:



1. From Table 1.1, $E_0 = -0.763\text{V}$ vs. standard hydrogen electrode

2. $n = 2$ (see Table 1.3)
3. From a table of activity coefficients found in engineering handbooks, $a_M^{+ne} = 0.71$ for zinc chloride at a molar concentration of 0.01
4. The activity of pure zinc, $a_M = 1$

$$E = -0.763 + \frac{0.059}{2} \times \log \left(\frac{0.71 \times 0.01}{1} \right)$$

$$\therefore E = -0.827 \text{ V}$$

Table 1.3 Valence of Common Metals

Metal	Valence
Aluminum	3
Copper	2
Iron	3
Iron	2
Lead	2
Zinc	2

Later in the course, various experiments will be conducted that involve the measurement of metal potentials with reference to a copper-copper sulfate reference electrode. Your results might be slightly different from the data in published tables because of differences in ion concentration between the table and the experiments. The higher the concentration of metal ions, the less active (or more noble) the metal.

Temperature Differences

In a temperature cell, the anode and cathode are of the same metal, but one is maintained at a higher temperature than the other by some external means. In most cases, the electrode at the higher temperature becomes the anode.

A gas transmission line emerging from a compressor station serves as an example. The just-compressed gas is hot and, as it travels down the line, the pipe loses heat by transfer to the surrounding soil (as well as losing some by expansion). The hot pipe near the compressor is the anode; the cooler pipe down the line is the cathode; the soil is the electrolyte; and the pipe itself is the connecting circuit. This is a particularly difficult type of corrosion cell because the high temperature just outside the compressor may damage the coating, so that the part of the line that is the anode also is likely to have the poorest coating. See Figure 1.5.

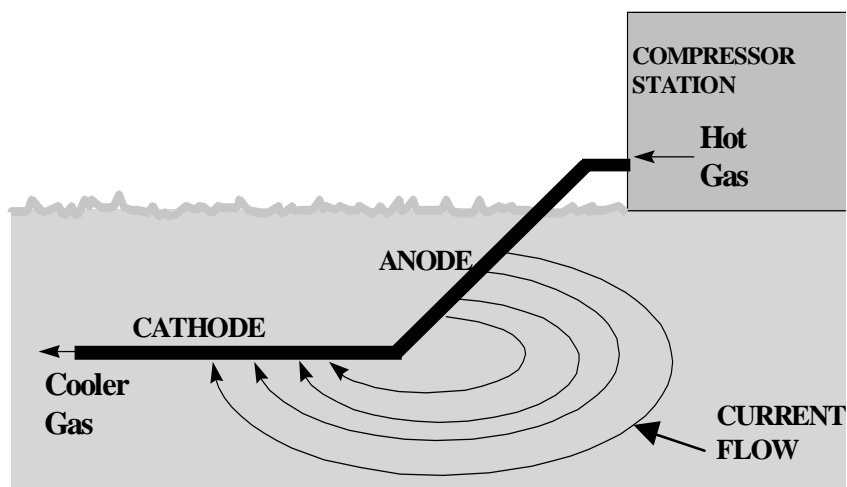


Figure 1.5 Temperature Difference Along a Metal Structure

Oil and gas well casings also experience similar corrosion cell attack. The pipe casing deep below the surface is at a higher temperature than the pipe near the surface and thus becomes the anode. (This is a natural phenomenon—temperature increases with depth.) The cooler pipe near the surface and the surface piping make up the cathode. The soil is the electrolyte and the pipe is the connection. Note that this cell operates in the same direction as the oxygen cell that will be discussed later in this chapter. Both tend to concentrate the corrosion on the deeper portion of the casing.

Effects of Alloying

During the process of alloying, the grain boundaries can become enriched or depleted of specific alloying elements. These differences in alloy composition may cause intergranular corrosion. Another common corrosion problem found in some alloys involves selective leaching, corroding of the more active alloying element in the solid matrix, such as zinc leaching from brass alloys or iron leaching from cast iron.

During the fabrication of structures, metals may experience variations in stress. Highly stressed areas of a metal will tend to be at higher energy levels, thus more active than less stressed areas. Also, improper welding procedures may be responsible for corrosion due to incompatibility of welding rods or sensitizing of the adjacent metal.

Electrolyte

The physical properties of an electrolytic environment may fall any place between a liquid (water) and a solid (concrete). Soils, which are a mixture of solids, liquids, and gases, are classified by the particle size distribution.

Corrosion cells may form because of differences in the electrolyte. For example, when a single metal structure spans an electrolyte made up of different types of soils, different chemical substances, different concentrations of the same substance, or temperature variations, the structure may experience voltage differences (see Figure 1.6). Another example of this is a reinforced concrete bridge deck where the top layer of reinforcing steel is exposed to salt contamination. A macro corrosion cell develops between the top rebar in salt-containing concrete and the bottom rebar layer in uncontaminated concrete.

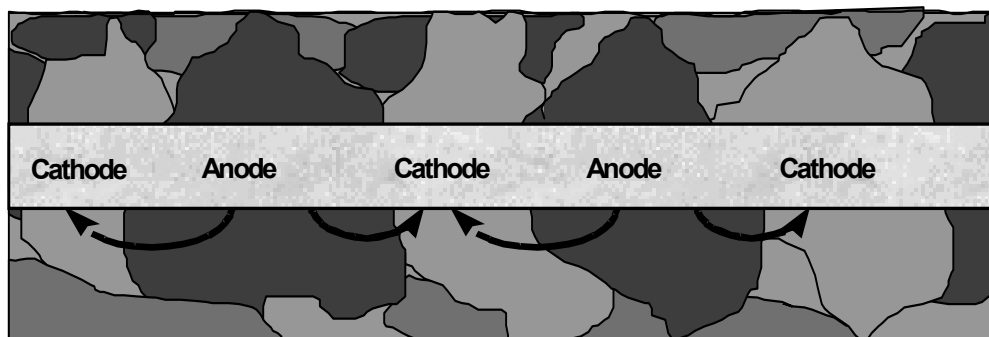


Figure 1.6 Corrosion Cells in Dissimilar Soils

If one electrolyte is a dilute salt solution and another is a concentrated salt solution, a concentration cell may form. This takes place because one of the factors determining an electrode potential is the electrolyte concentration. A similar cell is formed when the two electrolytes contain entirely different dissolved substances.

Concentration Cells

Concentration cells are responsible for much of the corrosion that takes place in soils. Pipelines, for example, pass through different soils on their way across the land. Oil and gas well casings penetrate various strata of different compositions. In every case of different soils in contact with a single piece of metal, a concentration cell is possible. This is particularly true for bare or poorly coated pipe.

In many cases in naturally occurring soils, that portion of pipe lying in the more conductive soil is the anode; that in the less conductive soil is the cathode. Moist soils themselves act as the electrolyte (in this case, a compound electrolyte) and the pipe itself is the connecting circuit between the anode and cathode sites. The current flows from the anodic area to the soil, through the soil and from it to the cathodic area, then along the pipe to the anodic area, as shown in Figure 1.7.

Types of Concentration Cells

When a simple salt is involved, and is not a salt of the metal that makes up the electrodes, the electrode in the higher concentrated solution may be the anode, as shown in Figure 1.7. When the electrolyte contains a salt that is of the metal and no other salts are present, then the metal surface in the dilute solution usually is the anode.

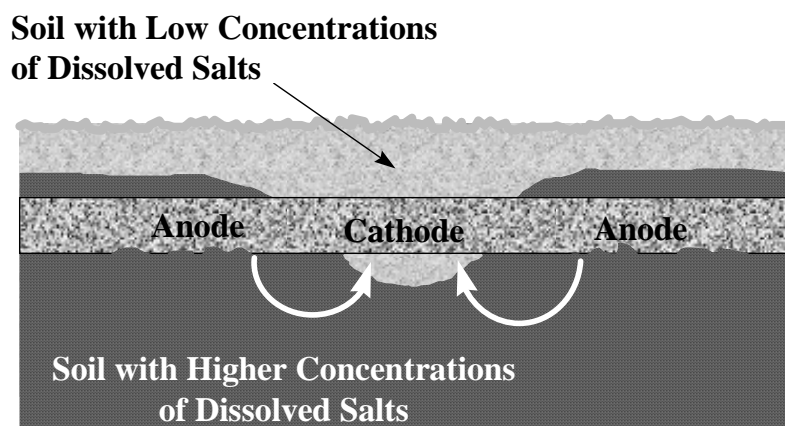


Figure 1.7 Ion Concentration Cell

The two most common types of concentration cells involved in promoting corrosion are oxygen and metal ion.

Oxygen Concentration Cell

Oxygen is the most common of the cathodic depolarizers. The oxygen content of any electrolyte ranks high on the list of factors influencing the corrosion of iron and numerous other metals. Oxygen can maintain and promote a cathodic reaction.

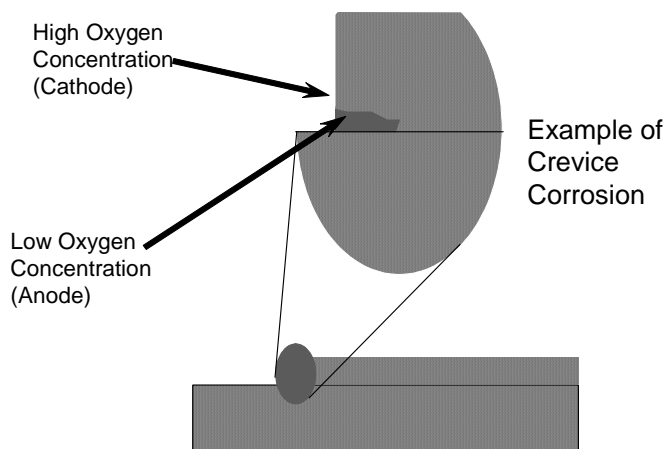


Figure 1.8 Oxygen Concentration Cell

Surfaces in contact with the solution containing a higher concentration of oxygen will become cathodic, as shown in Figure 1.8.

Oxygen concentration cells may occur on buried pipes. For example, the pipe usually rests on undisturbed soil at the bottom of the ditch. Around the sides and on the top of the pipe is relatively loose backfill that has been replaced in the ditch. Because the backfill is more permeable (than undisturbed earth) to oxygen (and the path is shorter) diffusing down from the surface, a cell is formed. The anode is the bottom surface of the pipe, and the cathode is the rest of the surface. The electrolyte is the soil, and the connecting circuit is the pipe metal itself. This explains why most corrosion on pipelines is on the bottom portion of the pipe.

When buried metal passes under pavement, such as an airport runway, parking lot, or street, as shown in Figure 1.9, the portion of the piping under the pavement has less access to oxygen than the piping in the unpaved soil. Thus a cell is formed: the anode is the metal under the pavement; the cathode is the metal outside the pavement; the electrolyte is the soil; and the connecting circuit is the metal itself. Although the entire length of pipe under the pavement could be anodic, most of the attack will take place not far from the edge of the pavement where the oxygen concentration difference is greatest.

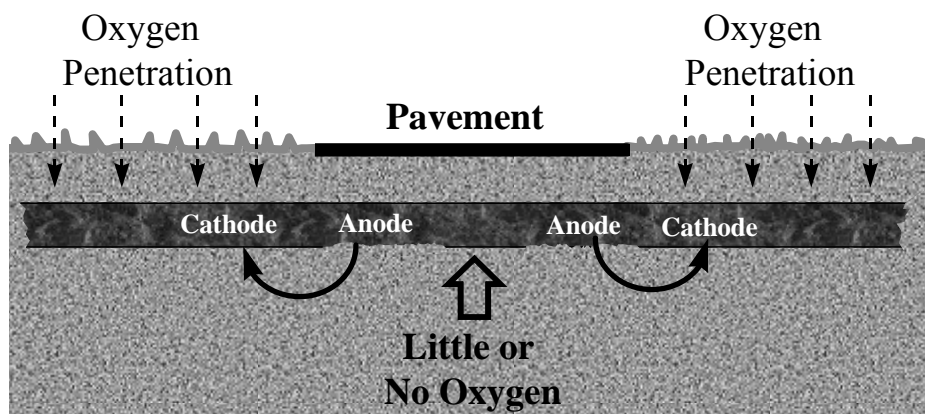


Figure 1.9 Oxygen Concentration Cell Example

The casing of an oil or gas well usually is connected to a network of surface piping, which lies just below the surface. This can form an oxygen concentration cell: the casing, at depth, forms the anode; the surface piping, with greater access to oxygen, becomes the cathode; again, the soil is the electrolyte; and the piping and casing together make the connecting circuit. Isolating the surface piping from the casing by means of a special isolating union or fitting can control the action of this cell.

Oxygen concentration cells are responsible for much of the corrosion near the water line on piling driven into the bed of the sea or in fresh water bodies. Wave action maintains a constant supply of oxygen to the metal just below the surface, while at greater depths there is little oxygen penetration.

Metal Ion Concentration Cell

Metal ion concentration cells exist where there is a lower concentration of ions at one point on a metal surface and a higher concentration at another point.

The surface in contact with lower concentration of metal ions acts as the anode.

Effects of pH

Theoretically, the potential of a structure changes by about 60 mV for each pH unit. For example, the corrosion potential (E_{CORR}) of a metal might be -500 mV in an environment with a pH of 7, but the value of E_{CORR} will be -560 mV at a pH of 8. This can lead to galvanic corrosion cells caused by differences in environment pH.

Environments with an acidic pH can also be harmful to concrete, such as reinforced concrete structures and concrete coated structures (e.g., pipes). The acid dissolves the alkaline components in the cement paste causing the concrete to fall apart. A pH less than 5 is considered harmful to concrete.

Corrosion Rate

The rate of corrosion is directly proportional to current flow. This section will examine factors that affect current flow as well as current density. Current density is more important in gauging the potential destructiveness caused by current flow.

Faraday's Law

Faraday's Law relates weight loss of metal in a corrosion cell with time and current flow. The law is expressed in the following formula:

$$W = \frac{M t I}{n F} \quad \text{Eq. 1-3}$$

where:

W	= weight loss of corroding metal (grams)
M	= atomic weight of the metal
t	= time during which current flows (seconds)
I	= current flow (A)
n	= number of electrons transferred per atom of metal
F	= Faraday's constant (96,500 coulombs per equivalent)

Another form of Faraday's Law is given by the following equation:

$$W = K I t \quad \text{Eq. 1-4}$$

where:

W	= weight loss, kg or lbs
K	= electrochemical equivalent, kg/A-yr or lb/A-yr
I	= current, A
t	= time

Table 1.4 Electrochemical Equivalents

Reduced Species	Oxidized Species	Molecular Weight, M (g)	Electrons Transferred (n)	Equivalent Weight, M/n (g)	Theoretical Consumption Rate (Kg/A-y)
Al	Al ⁺⁺⁺	26.98	3	8.99	2.94
Cd	Cd ⁺⁺	112.4	2	56.2	18.4
Be	Be ⁺⁺	9.01	2	4.51	1.47
Ca	Ca ⁺⁺	40.08	2	20.04	6.55
Cr	Cr ⁺⁺⁺	52.00	3	17.3	5.65
Cu	Cu ⁺⁺	63.54	2	31.77	10.38
H ₂	H ⁺	2.00	2	1.00	0.33
Fe	Fe ⁺⁺	55.85	2	27.93	9.13
Pb	Pb ⁺⁺	207.19	2	103.6	33.9
Mg	Mg ⁺⁺	24.31	2	12.16	3.97
Ni	Ni ⁺⁺	58.71	2	29.36	9.59
OH	O ₂	32.00	4	8.00	2.61
Zn	Zn ⁺⁺	65.37	2	32.69	10.7

Example:

If a 1 A CP system must last 40 years and the electrochemical equivalent for silicon chromium cast iron anodes is 0.75 lb/A-yr, how many pounds of anodes are needed?

$$\begin{aligned}
 W &= K I t \\
 &= 0.75 \text{ lb/A-yr} \times 1 \text{ A} \times 40 \text{ years} \\
 &= 30 \text{ lbs}
 \end{aligned}$$

Voltage Difference

Regardless of the source of the voltage difference, the greater the magnitude of the difference, the higher the current flow and rate of corrosion, all other things being equal.

For example, magnesium will corrode at a faster rate when connected to steel rather than zinc, simply because the voltage difference between magnesium and steel is greater than that between magnesium and zinc.

A voltage can be measured between different metals in an electrolyte or from a metal to a reference electrode both contacting the same electrolyte.

Reference Electrodes (Half-Cells)

General

Reference electrodes, or half-cells, are important devices that permit measuring the potential of a metal surface exposed to an electrolyte. The standard hydrogen electrode (SHE) is considered a primary reference electrode because it is used to determine the potential of other (secondary) reference electrodes that are better suited for field use. A structure-to-electrolyte potential is actually the potential difference between the structure and a reference electrode. The electrolyte itself

has no potential value against which the potential of a structure can be measured independently of the potential of the reference electrode used. Therefore, before discussing how to measure potentials along a structure, we must discuss reference cells.

Standard Hydrogen Electrode

There are several potential benchmarks in common use, but all of them are related to a basic standard. In this standard one-half of the cell generating the potential to be measured is represented by a platinized electrode over which hydrogen gas is bubbled while immersed in a solution having a definite concentration of hydrogen ions. If it is arbitrarily agreed that the potential of the platinized electrode covered with hydrogen in its standard solution is zero on a scale of potentials, then the potentials of all the other metals in their appropriate solutions can be described in terms of this reference.

The SHE half-cell is awkward to use in most circumstances in which potential measurements are to be made. Instead, other combinations of metal electrodes in solution with a specific concentration of ions are used. The reference cell must be stable and capable of producing reproducible data.

Copper-Copper Sulfate Electrode

Copper sulfate reference electrodes (CSE) are the most commonly used reference electrode for measuring potentials of underground structures and also for those exposed to fresh water. It is not suitable for use in a chloride electrolyte as the chloride ions will migrate through the porous plug and contaminate the CSE. The electrode is composed of a copper rod, immersed in a saturated solution of copper sulfate, held in a non-conducting cylinder with a porous plug at the bottom, as shown in Figures 1.10 and 1.11. The copper ions in the saturated solution prevent corrosion of the copper rod and stabilize the reference electrode.

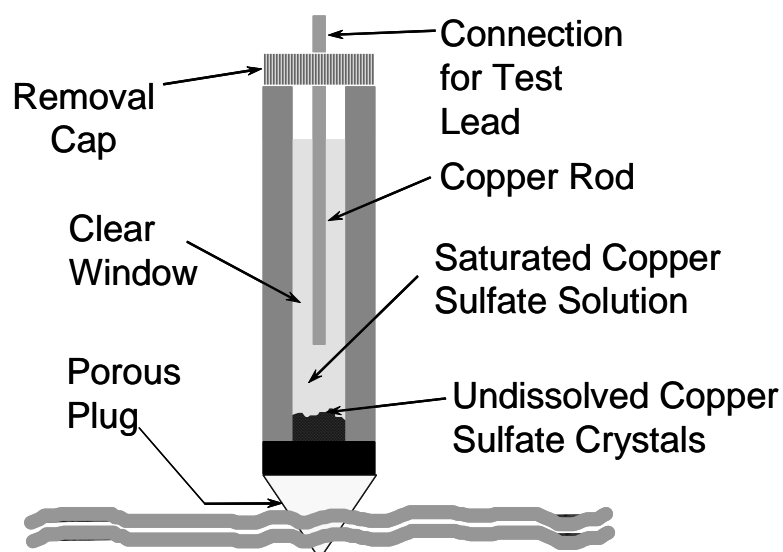


Figure 1.10 Copper-Copper Sulfate Reference Electrode in Contact with Earth



Figure 1.11 Portable Copper-Copper Sulfate Reference Electrodes

Use and Care of Copper Sulfate Reference Electrodes

- Keep clean.
- Keep the plastic/rubber cap on the porous plug when not in use.
- Periodically clean the porous plug to prevent clogging the pores.
- Keep free of contamination.

- Periodically replace copper sulfate and clean copper rod with a nonmetallic abrasive material; use silica sandpapers, for example, not an aluminum oxide paper to clean the rod. If the solution becomes cloudy, clean it out and replace with fresh copper sulfate solution.
- Be certain there are always undissolved crystals in the solution; this creates a super-saturated solution in which the copper will not corrode and thus will be stable.
- Perform maintenance after electrode has been used in a situation where contamination could have occurred (e.g., salt water). Chloride contamination changes the chemical reactions and the reference potential becomes a lower composite with the error being -20 mV at concentrations of 5 ppt and -95 mV at concentrations of 10 ppt.
- Keep a few spares on hand. Electrodes do get lost now and then.
- Keep one fresh electrode in the office or shop to be used to calibrate your field electrodes, preferably daily. Clean or replace field electrodes if they are more than 5 mV different from your calibrating electrode.
- Correct for potential variations due to temperature. Record the temperature when taking readings in the event temperature correction is needed. A temperature correction of 0.5 mV/ $^{\circ}\text{F}$ or 0.9 mV/ $^{\circ}\text{C}$ must be either added or subtracted when reference temperature is above or below ambient temperature, respectively.
- Shield the electrode from direct sunlight during measurements (e.g., place dark tape over clear strip on side of electrode). The potential of a reference electrode in the sun can decrease from 10 to 50 mV versus an electrode kept in the dark.

Other Reference Electrodes

Silver-Silver Chloride Reference Electrode

Silver-silver chloride (Ag-AgCl) reference electrodes are used for measurements in seawater. The Ag-AgCl electrode is also used in concrete structures. There are two types; in one type the silver electrode is exposed to seawater and in the other the electrode is immersed in a potassium chloride (KCl) solution contained in a cylinder with a porous plug. A correction must be made to readings taken with the first reference if not in pure seawater (see NACE Standard RP0176, Figure 1).

Calomel Reference Electrode

The saturated calomel reference electrode consists of mercury-mercurous chloride in a saturated potassium chloride solution. This is primarily a laboratory electrode.

Zinc Reference Electrode

Zinc is sometimes used as a reference electrode since the potential of zinc is relatively stable. Zinc is actually a pseudo-reference electrode since the potential of zinc can change as the environment changes. Zinc is not stable in carbonates or at high temperatures.

For underground use, the zinc electrode is packaged in a cloth bag containing the same backfill as used around zinc anodes. In water, zinc electrodes are used bare.

Manganese Dioxide

The manganese dioxide electrode is used in reinforced concrete structures.

Graphite Electrode

Graphite is a pseudo-reference electrode that is sometimes used in reinforced concrete structure.

Polarity

It is imperative that the polarity of a measurement be noted and recorded. Since most instruments used today are digital with automatic polarity display, a CP Tester or Technician may not be as concerned with the sign of the reading when connecting the voltmeter for the measurement. It is still important to pay attention to the connection of the instrument terminals and the expected sign in order to detect problems during a survey. Most digital meters will display a negative sign for a negative reading and no sign for a positive reading. When a voltmeter is connected across a metallic element, such as a wire or pipeline with external current flow, the voltage display is positive when the positive terminal of the voltmeter is upstream of the direction of current as illustrated in Figure 1.12.

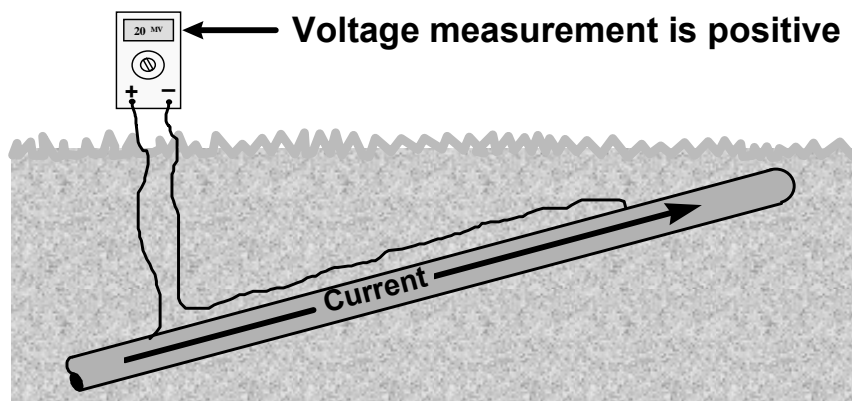


Figure 1.12 Current Direction

If a voltmeter is connected such that the positive terminal is connected to the more noble metal and the negative terminal to the more active metal, then the reading is positive (see Figure 1.13). Current will go from the active to the noble metal through the electrolyte and from the noble to the active metal through the metallic path. Therefore, the reading is positive because conventional current is going into the positive terminal of the voltmeter.

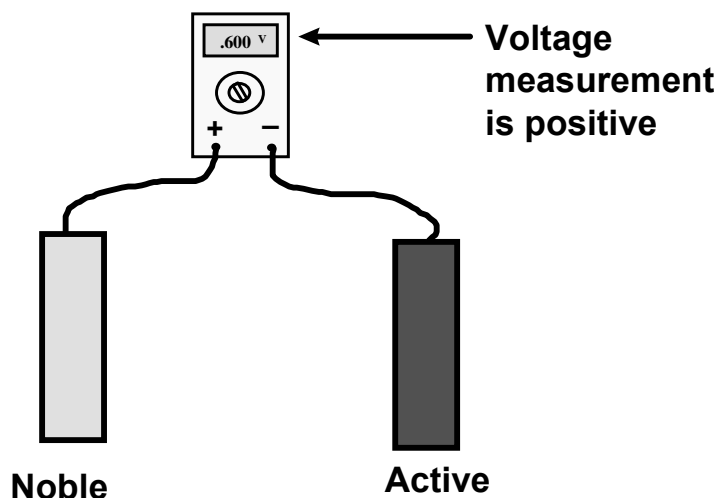


Figure 1.13 Measurement of a Noble Metal and an Active Metal Immersed in an Electrolyte

The term structure-to-electrolyte potentials suggests that the structure is being measured with respect to a reference in the electrolyte thus the structure is connected to the positive terminal and the reference is connected to the negative terminal. If the meter indicates the reading is negative then it is recorded as such. A digital voltmeter indicates a negative reading with a negative sign. On an analog meter, the needle will swing to the right when the reading is positive. When using an analog meter with a center zero, with the reference electrode to

the negative terminal, the needle will swing to the left, indicating the negative reading. With a left hand zero instrument, the needle will pin unless the leads are reversed or a polarity switch is available. The meter will now read to the right, but the leads or position of the switch will indicate that it is a negative reading and must be recorded as such.

Converting Between Reference Electrode Values

A potential measured using any of these reference electrodes can be converted easily to a value that corresponds to a different reference electrode.

Relative electrode values vary but the values used for this course are shown in Table 1.5.

Table 1.5 Relative Values of Typical Reference Electrodes to a Hydrogen Electrode

Electrode (Half-Cell)*	Potential (volt)
Standard Hydrogen	0.000
Copper-Copper Sulfate (CSE)	+0.316
Silver-Silver Chloride (SSC)	+0.256
Saturated Calomel (SCE)	+0.241
Zinc (ZRE)	−0.800

The graphical method is illustrated using the scale in Figure 1.14 for an original potential of -0.810 mV measured on a metal "X" with respect to a copper-copper sulfate reference electrode (CSE).

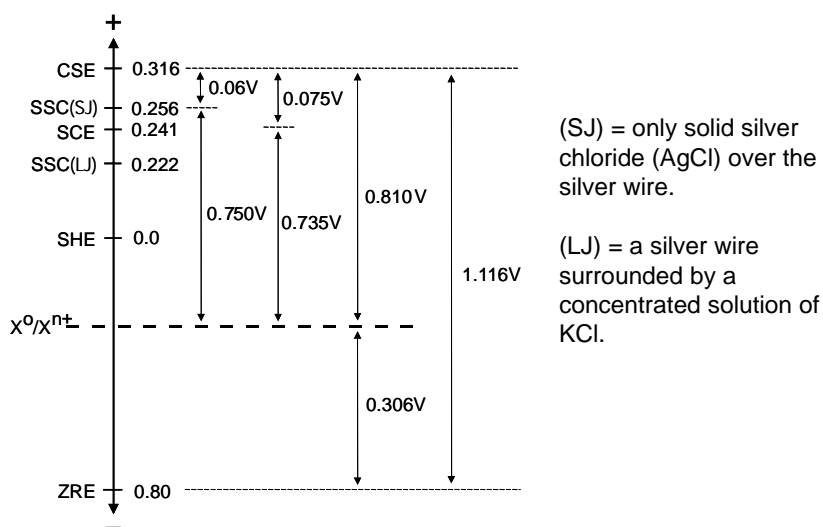


Figure 1.14 Reference Electrode Conversion Scale

For a potential of $-0.800 V_{\text{CSE}}$, the measurement of an unknown metal electrode X^0/X^{n+} with respect to a CSE electrode converts to the following potentials with respect to other secondary reference electrodes:

$$X^0 / X^{n+} /_{\text{SCE}} \text{ is } -0.810 V_{\text{CSE}} - (-0.075 V_{\text{SCE}}) = -0.735 V_{\text{SCE}} \quad \text{Eq. 1-5}$$

$$X^0 / X^{n+} /_{\text{SSC}} \text{ is } -0.810 V_{\text{CSE}} - (-0.060 V_{\text{SSC}}) = -0.750 V_{\text{SSC}} \quad \text{Eq. 1-6}$$

$$X^0 / X^{n+} /_{\text{ZRE}} \text{ is } -0.810 V_{\text{CSE}} - (-1.116 V_{\text{ZRE}}) = +0.306 V_{\text{ZRE}} \quad \text{Eq. 1-7}$$

This conversion process can be completed arithmetically by the following steps:

1. Determine the potential difference between the first reference electrode and the second reference electrode (e.g., CSE is +75 mV to SCE).
2. Add the original potential difference to obtain the converted potential.

$$\begin{aligned} \text{e.g., } X^0 / X^{n+} /_{\text{SCE}} &= +75 \text{ mV} + (-810 \text{ mV}_{\text{CSE}}) \\ &= -735 \text{ mV}_{\text{SCE}} \end{aligned}$$

STUDENT PRACTICE CALCULATIONS

Given Structure-to-electrolyte in reference to CSE = -0.87 V

Calculate Structure-to-electrolyte in reference to the following electrodes using the values in Table 1.5.

Silver-Silver Chloride = _____

Saturated Calomel = _____

Zinc = _____

Portable vs. Stationary Electrodes

Portable reference electrodes can, as the name applies, be transported from one location to another. These are used for field and laboratory testing purposes and can be maintained regularly (cleaned and refilled).

Stationary (formerly called permanent) reference electrodes are intended for installation in or near a structure (i.e., buried next to a tank or pipe, embedded in concrete, or installed inside a waterbox) to monitor the structure-to-electrolyte potential. These electrodes cannot be moved from location to location and cannot be maintained after installation. Stationary electrodes remain calibrated only for a particular length of time and will eventually become unusable. The potential of a stationary reference electrode should be checked from time to time with a portable reference electrode that is known to be accurate under “no current” conditions.

Polarization

As current is impressed on a metal over time, polarization occurs at both the anode and cathode. Polarization lowers the potential difference between the anode and cathode areas and, by Ohm’s Law, the current, I , drops and the corrosion rate decreases until an equilibrium is reached between polarization and depolarizing effects. Depolarizers include:

- dissolved oxygen
- microbiological activity
- water flow

Polarization always occurs in the direction to oppose the current flow causing it. When the anode and cathode of a corrosion cell are connected, the resulting

current will cause the potential of the anode to approach the potential of the cathode and the potential of the cathode will approach the potential of the anode. As the resistance of the electronic and/or electrolytic paths reduces, the voltage difference between the polarized electrodes also reduces, and both electrodes come to a steady state polarized potential. However, in the real world there will always be resistance in the current paths, so the mixed potential is somewhere between the polarized potentials of the two electrodes. The difference between the polarized potentials of the anode and cathode is the driving voltage of the corrosion cell. The current at this steady state condition is defined as the *corrosion current* (I_{CORR}) of the system. The potential normally measured is a mixed potential (E_M) between the polarized cathode potential (E_{pc}) and the polarized anode potential (E_{pa}).

Figure 1.15 graphically illustrates the concept of polarization. Such diagrams are called *Evans diagrams*. *Open circuit potentials*, are the potentials of the cathode and anode, E_{OC} and E_{OA} , when the corrosion current is zero. E_{PA} is the polarized potential of the anode and E_{PC} is the polarized potential of the cathode. I_{CORR} is the corrosion current of the corrosion cell. As the current is increased, the value of E changes either anodically or cathodically depending on current direction.

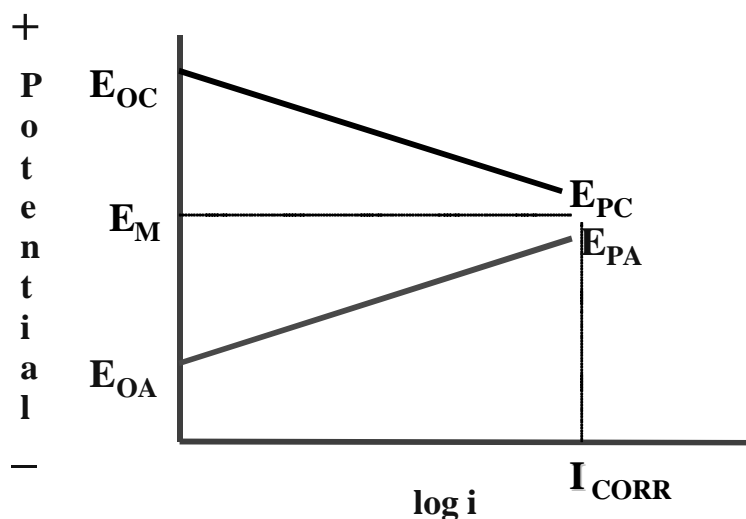


Figure 1.15 Polarization Diagram (Evans Diagram)

In general, polarization is related to the depletion of the reactants and the buildup of reaction products. Anything that favors the buildup of reaction products or the depletion of reactants increases polarization. Conversely, anything that causes the removal of reaction products or the replenishing of the reactants will reduce polarization or depolarize.

There are two types of polarization—activation and concentration.

Activation polarization is the result of the reaction steps at the structure/electrolyte interface including the actual transfer of charge. These are the reaction steps occurring after all of the necessary reactants are in place at the interface and are ready to take place. The charge transfer reaction involves moving an electron from the metal surface to the reactant on the electrolyte side of the interface. If the charge transfer reaction or any reaction step on the metal surface is the slowest step in the overall reaction process, the process is under activation polarization.

Activation polarization usually predominates initially or in electrolytes where abundant reactants and/or products involved in the electrochemical reaction are easily removed. In concentrated acids, activation polarization predominates.

Concentration polarization is the result of reaction steps involving the diffusion of reactants up to or the reaction products away from the reaction surface (structure interface). Anything that causes a depletion of available reactants or a buildup of reaction products results in a decrease in the reaction rate and an increase in concentration polarization. If the slowest step in the overall process involves waiting for arrival of reactants or the removal of reaction products, the reaction is under concentration polarization control.

Concentration polarization usually predominates in electrolytes where the concentration of the reactants is low, as with dilute solutions, or there is a buildup of reaction products from activation polarization or in stagnant environments.

The ability of the reactants to reach the reacting surface and the reaction products to move away from the reacting surface determines the limiting current density.

The total polarization of a structure is the sum of the activation and concentration polarization.

With the application of the first increments of CP current, the reaction rate is relatively slow, the reactants are plentiful and the reaction products can move away with sufficient speed to avoid blocking the reacting surface. In this case the structure is most likely under activation control. However as the CP current is increased, the availability of reactants at the interface decreases and the reaction products start to accumulate and concentration polarization begins to control. As the current nears the limiting current density the potential at the

interface becomes more negative very fast. Unless another cathodic reaction is possible at the more negative potentials, the reaction rate reaches the limit and the current density cannot increase further.

If another cathodic reaction becomes possible, the current density can continue to increase with the availability of new reactants. This can occur for steel under CP in neutral aerated soils where oxygen reduction occurs at first up to the limiting current density and then water electrolysis occurs as the potentials become more negative (Figure 1.16).

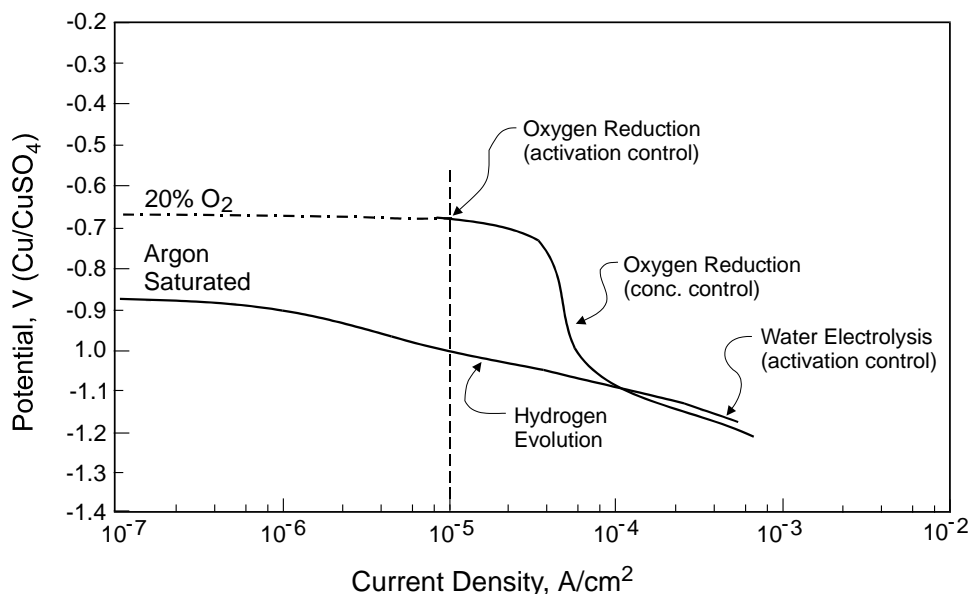


Figure 1.16 Polarization Curves in Aerated and Deaerated Solutions of pH 7

Source: N. G. Thompson and T. J. Barlo, "Fundamental Processes of Cathodically Protecting Steel Pipelines," Gas Research Conference Proceedings, presented 1983 (Rockville, MD: Government Institutes, Inc.).

Note that there is little potential change under activation control while there is a rapid change under concentration control.

IR Drop

Polarization measurements include a voltage ("IR Drop") component that is produced by current, I , through electrolyte to the electrode. Similar to the voltage produced across a resistor with current. The IR component occurs across the soil or the structure interface, or both. Whereas polarization decays at measurable rates once the current is interrupted the IR component disappears instantly. This IR component is not polarization and must be taken into consideration or eliminated from measurements when the potential is used to meet a criterion.

Factors Affecting Polarization

Several factors affect polarization:

- Current (charge transfer)
- Electrolyte resistivity (total ion concentration)
- Anode/Cathode Ratio
- Temperature effect
- Relative electrolyte/electrode movement effect
- Electrolyte concentration effect

Current (Charge Transfer)

Since polarization is caused by current, then as current increases, polarization increases. A greater current results in a high reaction rate, causing a depletion of reactants and a buildup of reaction products. It may be a little confusing, but remember where the controlling factor is current, an increase in current causes an increase in polarization, but where the controlling factor is polarization, an increase in polarization will cause a decrease in current.

Electrolyte Resistivity (Total Ion Concentration)

Since the transfer of current (charge) through the electrolyte depends on ions, the total number of ions present will have a significant impact on the electrolyte resistivity and therefore on the current flow in the circuit. An increase in ions will result in a decrease in resistivity.

Anode/Cathode Ratio

Polarization is a function of the current density or current per unit area. The effect of current concentrated on a small area will be greater than the effect of the same amount of current on a larger area. For example, a coated structure will polarize more rapidly than a bare structure with a given amount of current.

Area effect is also a concern when considering the destructiveness of corrosion. If the current is small, the metal loss due to corrosion is also small but if concentrated in a small area a pit results that is more destructive to structures than a larger loss of metal due to uniform corrosion. For a corrosion cell, the area ratio of the anode and cathode is important. A small anode and large cathode is undesirable because the pitting is greater compared to a large anode and small cathode.

Temperature

Temperature affects the kinetics of both the anodic and cathodic reactions. In other words, an increase in temperature has a tendency to speed up chemical reactions, which depolarizes the electrodes and increases current. Likewise, a decrease in temperature results in an increase in polarization. The following polarization diagram (Figure 1.17) illustrates the effect of temperature on current flow.

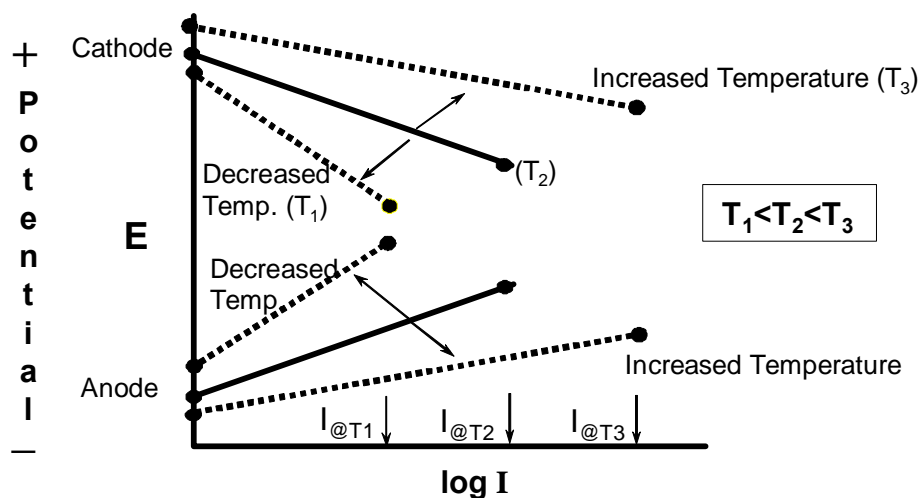


Figure 1.17 Effect of Temperature (T) on Polarization

Electrolyte/Electrode Movement Effect

Increased movement between the electrodes and the electrolyte, whether caused by electrolyte agitation or electrode vibration, serves to remove reaction products at the anode and cathode, replenishing reactants at the cathode surface. Increased movement results in a decrease in polarization and an increase in current. In stagnant electrolytes the movement decreases, causing an increase in polarization and a decrease in current, as shown in Figure 1.18.

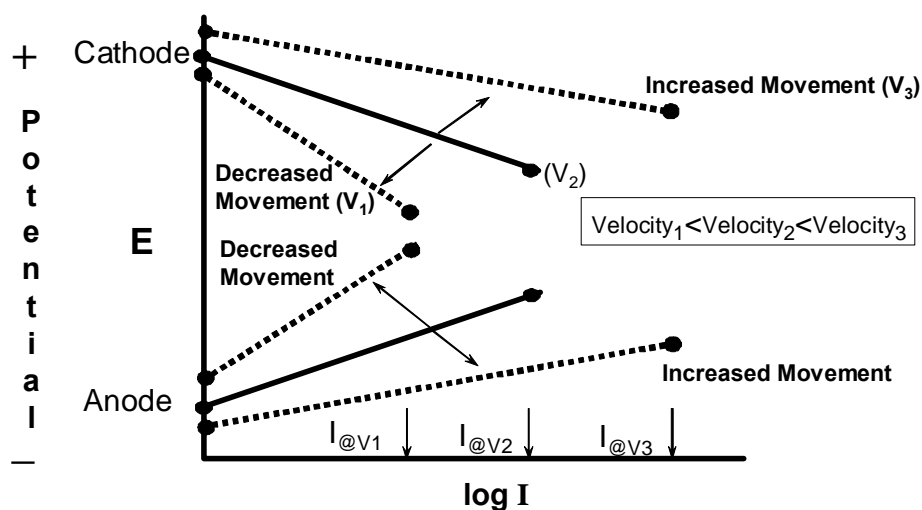


Figure 1.18 Effect of Electrolyte/Electrode Movement (V) on Polarization

Electrolyte Concentration Effect (Interface Area)

Anodic Polarization

Polarization of the anode can be affected by the concentration of the corroding metal ion, M^{+ne} , the product of the metal oxidation (Figure 1.19). An increase in the metal ion concentration of the anode metal results in an increase in polarization of the anode and a decrease in current. Likewise, a decrease in anode metal ions causes a decrease in polarization of the anode and an increase in current.

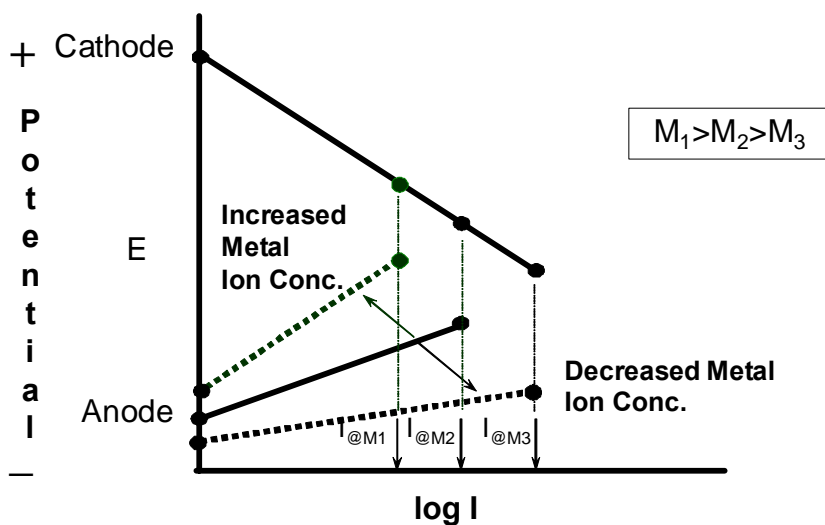


Figure 1.19 Effect of Corroding Metal Ion Concentration (M_x)

Cathodic Polarization

Polarization of the cathode can be affected by the concentration of cathodic reactants, such as oxygen or hydrogen ions. An increase in the concentration of either of these reactants will decrease polarization of the cathode and increase current and vice versa. The next two diagrams illustrate the effect of changing the concentration of cathodic reaction reactants (Figures 1.20 and 1.21).

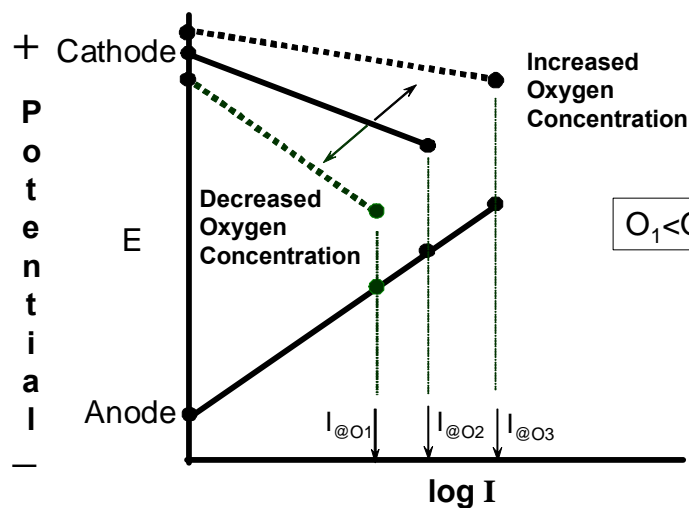


Figure 1.20 Effect of Oxygen Concentration (O_x) on Cathodic Polarization

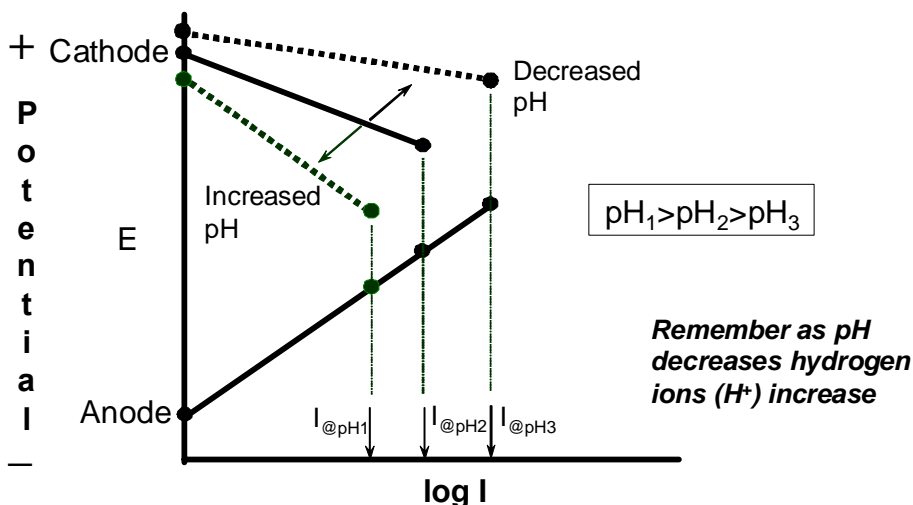


Figure 1.21 Effect of pH on Cathodic Polarization

Passivity

Passivity can be defined as the loss of chemical reactivity:

- exhibited by specific metals and alloys
- under specific environmental conditions
- caused by the formation of a surface film
- acts as a barrier to further corrosion.

Certain metals and alloys such as stainless steels, chromium, titanium and nickel alloys can become essentially inert and act as if they were noble metals under certain environmental conditions.

Passivating vs. Nonpassivating

One way of showing the unusual characteristics of a metal or alloy that demonstrates passivity is to compare it with a metal that does not show this effect.

Figure 1.22 illustrates passivating vs. nonpassivating metals by their anodic polarization behavior.

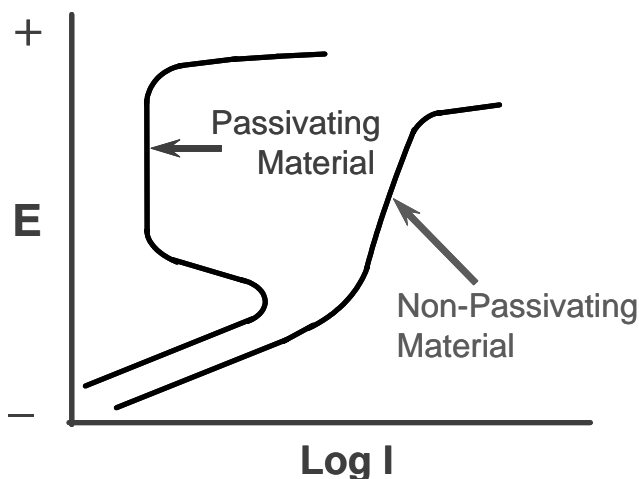


Figure 1.22 Passivating vs. Nonpassivating Behavior

Note that for the passivating metal:

- initially, a slight increase in corrosion potential causes the corrosion current to increase. This is the *active* region.

- when the corrosion potential increases to a certain point, however, the corrosion current suddenly decreases and remains essentially constant. This is the *passive* region.
- eventually, if the potential is increased sufficiently, current again increases. This is the *transpassive* region.

For the active (or nonpassivating) metal, as corrosion potential increases, corrosion current increases, more or less logarithmically (or linearly on a semi-log graph).

Oxide films, which form naturally on most metals when they are exposed to the air, can provide substantial protection against further attack by many environments. If it were not for such films, many common metals, such as aluminum or stainless steels, would corrode rapidly in ordinary air and water.

Forms of Corrosion

Corrosion may be grouped into the following general forms:

Uniform Attack — This is a uniform type of corrosion with an even loss of metal over the entire area or a large area of the structure.

Crevice Corrosion — This type of corrosion occurs where two tightly spaced surfaces – either two metals or a metal and nonmetal – are exposed to a corroding environment. Holes, gasket surfaces, lap joints, surface deposits, and crevices are likely places for this type of corrosion.

Galvanic Attack — This corrosion occurs when two dissimilar metals are connected. The potential of the two metals creates a voltage difference, the driving force for corrosion.

Pitting – Localized corrosion that occurs over a small area of the metal surface and leaves holes in the surface. Pits can be isolated or closely spaced. Pits can be small or large in diameter.

Intergranular Attack — This is a local corrosion attack at the grain boundaries of an alloy. It is caused by a difference in element composition near the boundaries, compared to the rest of the alloy.

Selective Leaching — This type of corrosion involves the selective removal of one of the elements from an alloy. Examples of this type of corrosion are dezincification of brass and graphitic corrosion of cast iron.

Velocity Phenomena — This corrosion is associated with rapid movement of a corrosive fluid over a metal, removing corrosion products. It is recognized by the appearance of grooves, trenches, etc., in the direction of fluid flow.

Environmental Cracking — Environmental cracking results from the reaction of the metal with a corrosive environment and the presence of a stress. There are three types of environmental cracking:

- *Corrosion Fatigue* — results in fatigue of the metal under an alternating stress in a corroding media.
- *Hydrogen Embrittlement* — the reduction in ductility of the metal from hydrogen that has diffused into the metal.

➤ Hydrogen Damage

Atomic hydrogen generated at the surface by cathodic protection can diffuse into the metal. This atomic hydrogen can cause blistering of the metal, the formation of hydrides (in the case of titanium) that embrittle the titanium, and the embrittlement of steel (particularly high-strength steel), martensitic stainless steel, high-strength aluminum alloys (particularly 7,000 series), and prestressed concrete. The embrittlement of the metal can cause cracks to form, which can grow and cause the structure to fail.

The prevention of hydrogen embrittlement depends on keeping the potential below the hydrogen evolution potential, which depends on the pH. In general, hydrogen is generated in neutral environments at $-1,044 \text{ mV}_{\text{CSE}}$. The lower the pH, the lower the hydrogen evolution potential. For aluminum, the polarized potential must be kept below $-1,200 \text{ mV}_{\text{CSE}}$ to avoid alkali corrosion. For titanium, the maximum potential is $-700 \text{ mV}_{\text{SSC}}$ to prevent hydriding. Overprotection levels are discussed in some cathodic protection criteria documents and might differ from these somewhat. For prestressed concrete, polarized potentials more negative than $-1,000 \text{ mV}$ should be avoided.

Care must be taken in designing and operating cathodic protection systems where materials susceptible to hydrogen embrittlement are used to limit the structure-to-soil potential below the hydrogen evolution potential.

Stress Corrosion Cracking (SCC) — the cracking of a metal under an applied tensile stress in the presence of a corrosive environment. Many metals, including high-strength steel, aluminum (2,000 and 7,000 series alloys), stainless steels, and brass alloys are susceptible to SCC. Cathodic protection generally reduces or eliminates SCC because it stops the corrosion process. However, SCC of high-strength pipeline steels caused by cathodic protection has occurred. This type of cracking occurs in a narrow potential range (-525 to $-725 \text{ mV}_{\text{CSE}}$) at a pH between 8 and 10.5, and is more likely at higher temperatures. The cracking occurs because of the formation of carbonates and bicarbonates at the steel surface. Research in this area is ongoing .

Experiment 1.1

Investigation of Changes in Corrosion Cell Operation to Changes in the Electrolyte

The experimental arrangement shown in Figure 1.23 below can be used to demonstrate typical changes that can occur in an operating corrosion cell.

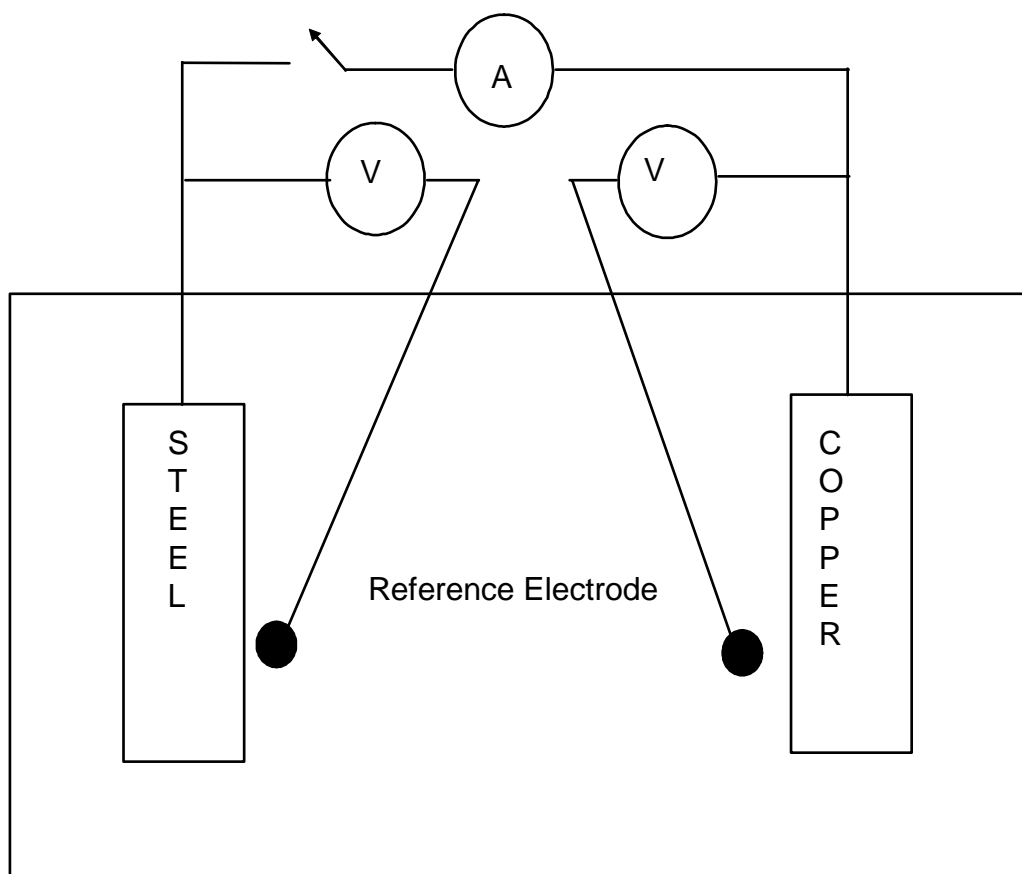


Figure 1.23 *Experiment to Show Effect of Environmental Changes on Corrosion Behavior*

In the following experiment both a cathodic depolarizer (hydrogen peroxide) and an anodic inhibitor (sodium nitrite) are used to cause polarization and open circuit potential changes at the anode and cathode, respectively. Changes in the corrosion cell current also occur.

PROCEDURE

Part A Set-up

1. Place tap water in tray.
2. Place steel sheet in left side of tray.
3. Place copper sheet in right side of tray.
4. Connect experimental circuit as shown in Figure 1.23.

Part B Cathodic Depolarization Effect of Hydrogen Peroxide

1. Measure open circuit potential of steel and copper using a copper sulfate electrode and a voltmeter.
2. Connect the two metals together using an ammeter and a pair of leads and record closed circuit polarized potential of steel and copper.
3. Measure corrosion current.
4. Add hydrogen peroxide solution to electrolyte at copper sheet (approximately 1 cap full) directly to the copper.
5. Repeat Steps 2 and 3.
6. Disconnect the ammeter and repeat Step B-1.
7. Empty electrolyte from tray.
8. Construct polarization (Evans) diagrams.

Part C Anodic Polarization Effect of Sodium Nitrite

1. With an empty tray, repeat Part A.
2. Repeat Part B, Steps 1, 2, and 3.
3. Add 2 capfuls of sodium nitrite inhibitor to the electrolyte at the steel anode.
4. Repeat Part B, Steps 2 and 3.
5. Disconnect the ammeter and repeat Part B, Step 1.
6. Empty electrolyte from tray.
7. Construct polarization (Evans) diagrams.

RESULTS

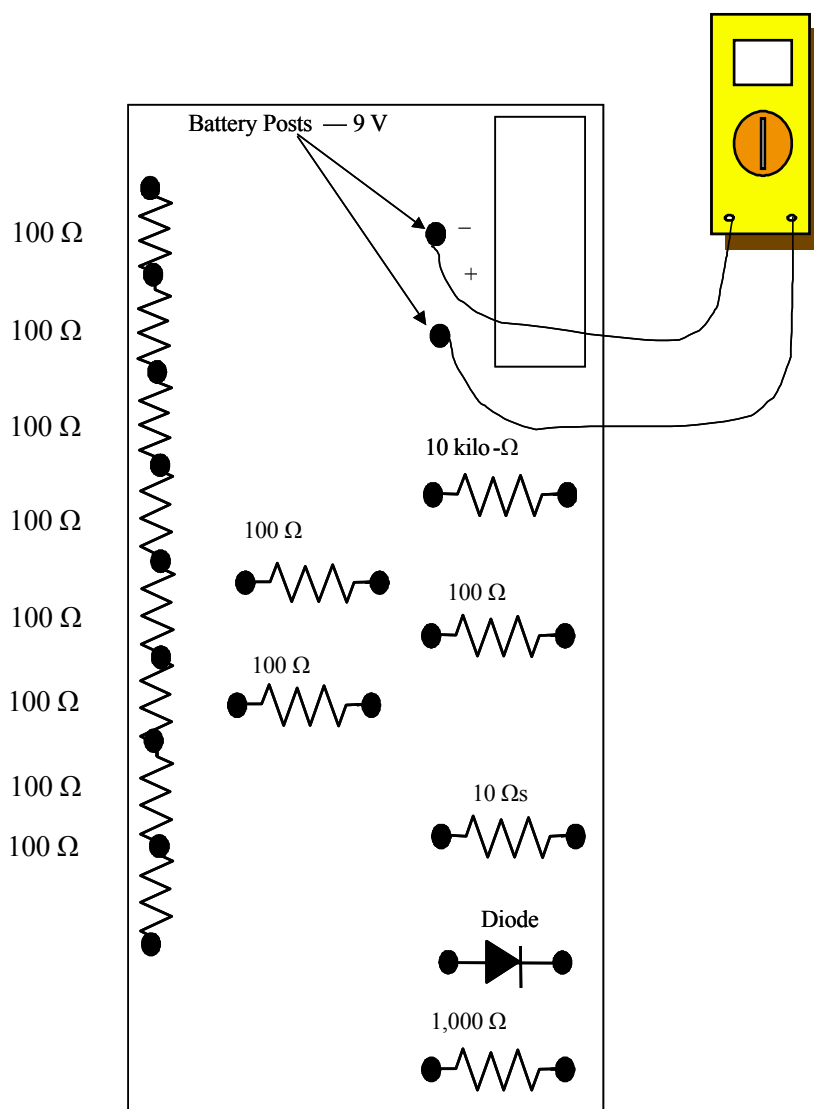
	E_{steel}	E_{copper}	I_{corr}
Part B			
Open Circuit			
Corrosion Cell			
Corrosion Cell (H_2O_2)			
Open Circuit (H_2O_2)			
Part C			
Open Circuit (OC)			
Corrosion Cell (CC)			
CC- Nitrite Added			
OC - Nitrite Added			

CONCLUSIONS

1. The addition of the hydrogen peroxide solution to the electrolyte at the copper cathode results in positive shifts of the anodic and cathodic polarization potentials and the cathodic open circuit potential. It also increases the corrosion cell current.
2. The addition of the sodium nitrite solution to the electrolyte at the steel anode results in positive shifts in the anodic and cathodic polarization potentials and the open circuit potential of the steel. It also decreases the corrosion cell current.

Exercise 1.1 Resistor and Instrument Lab

Simple measurements using the ammeter and voltmeter functions of a digital multimeter can be used to determine the characteristics and operating parameters of DC electrical circuits. The circuit board and digital multimeter contained in the experimental kits will be used for the following experiments. The circuit board layout is shown below.



Record the data collected on the Exercise 1.1 Data Sheet provided.

- Step 1.** Using the voltmeter, measure the voltage of the battery. Does it equal the printed battery voltage? If not, why?
- Step 2.** Using the ohmmeter, measure the resistance of each resistor. Do the resistances equal those marked on the resistors? If not, why?
- Step 3.** Calculate the total resistance (R_T).
- Step 4.** Wire the 1,000 Ω (R_2), 100 Ω (R_3), and 10 Ω (R_4) resistors below the battery in series and measure the total resistance (R_T) with the ohmmeter. [DO NOT CONNECT BATTERY] Does your measurement equal your calculation? If not, why?
- Step 5.** Using Ohm's Law and your measured values of E_T and R_T , calculate total current (I_T).
- Step 6.** With resistors still connected in series, connect the battery and the ammeter in series. [CAUTION: Make certain that the meter is set to mA scale before connecting battery.] Measure the total current (I_T). How does it compare with your calculated value?
- Step 7.** [SET METER TO VOLTS_{DC}] Measure the IR drop across each resistor and add them up and measure the source voltage. Does this sum equal the total measured voltage?
- Step 8.** Calculate the resistance of the 10 k Ω (R_1), 1,000 Ω (R_2), and 100 Ω (R_3) resistors below the battery in parallel.
- Step 9.** Wire the 10 k Ω (R_1), 1,000 Ω (R_2), and 100 Ω (R_3) resistors located below the battery in parallel and measure the total resistance, R_T . Is this value equal to the value calculated in Step 8? If not, why?
- Step 10.** Calculate the total current (I_T) through the parallel circuit described in Step 9.
- Step 11.** Measure the total current (I_T) with the ammeter. How does it compare with your calculation in Step 10?

Step 12. Calculate the current flow through the 10 k Ω (R_1), 1,000 Ω (R_2), and 100 Ω (R_3) resistors and the total current (I_T).

Step 13. Measure the current through each of the resistors 10 k Ω (R_1), 1,000 Ω (R_2), and 100 Ω (R_3) with the ammeter. How close do you come to your calculated value?

Step 14. Add the currents through each resistor. Do they equal the total measured or calculated current (I_T)? If not, why?

Step 15. Show current direction in each resistor. Was Kirchhoff's Current Law fulfilled?

DIODE CHECK

Check the diode with the diode checking circuit. Is it functioning properly?

EXERCISE 1.1 DATA SHEET

STEP 1 **RATED BATTERY VOLTAGE (E_T) :** _____ **V**

BATTERY VOLTAGE (E_T) : _____ **V**

STEP 2 **RESISTANCE MEASUREMENTS**

	<u>Nominal</u>	<u>Measured</u>
R_1	10,000 Ω	_____
R_2	1,000 Ω	_____
R_3	100 Ω	_____
R_4	10 Ω	_____

SERIES CIRCUIT

STEP 3

Calculated Total Resistance $R_T = R_2 + R_3 + R_4 =$ _____ Ω

STEP 4

Measured Total Resistance $R_T = R_2 + R_3 + R_4 =$ _____ Ω

STEP 5

Calculated Current (I_T) = E_T / R_T = : _____ **A**

STEP 6

Measured Current (I_T)= _____ **A**

STEP 7 MEASURED VOLTAGE DROPS

$V_1 =$: _____ V Across 1000 Ω resistor

$V_2 =$: _____ V Across 100 Ω resistor

$V_3 =$: _____ V Across 10 Ω resistor

Calculated Total $V_T =$: _____ V

Measured Source Voltage (E_T) : _____ Volts

PARALLEL CIRCUIT

STEP 8

Calculated Total Resistance $R_T = 1/(1/R_1 + 1/R_2 + 1/R_3) =$ _____ Ω

STEP 9

Measured Total Resistance $R_T =$ _____ Ω

STEP 10

Calculate Current (I_T)= $E_T/R_T =$: _____ A

STEP 11

Measured Current (I_T)= : _____ A

STEP 12 CALCULATE RESISTOR CURRENTS

$I_1 = E_T / R_1$: _____ V Across 10 k Ω resistor

$I_2 = E_T / R_2$: _____ V Across 1000 Ω resistor

$I_3 = E_T / R_3$: _____ V Across 100 Ω resistor

Calculated Total (I_T)= : _____ V

STEP 13 MEASURED RESISTOR CURRENTS $I_1 = : \underline{\hspace{2cm}} \text{ V Across } 10 \text{ k}\Omega \text{ resistor}$ $I_2 = : \underline{\hspace{2cm}} \text{ V Across } 1,000 \text{ }\Omega \text{ resistor}$ $I_3 = : \underline{\hspace{2cm}} \text{ V Across } 100 \text{ }\Omega \text{ resistor}$ **STEP 14**Calculated Total $I_T = : \underline{\hspace{2cm}} \text{ V}$ **STEP 15****DRAW SCHEMATIC AND INDICATE CURRENT DIRECTION (CLOCKWISE OR COUNTERCLOCKWISE) ON THE SCHEMATIC.**

DIODE CHECK

	FORWARD READING	REVERSE READING
Good	<input type="checkbox"/> <u> </u>	<u> </u>
Bad	<input type="checkbox"/> <u> </u>	<u> </u>
Shorted	<input type="checkbox"/> <u> </u>	<u> </u>

Concept of Cathodic Protection

Corrosion is the result of an electrochemical reaction driven by a potential difference between two electrodes, an anode and a cathode, connected by an electronic path and immersed in the same electrolyte (see Figure 2.1). In the case of uniform corrosion, a multitude of microscopic anodic and cathodic sites exist on the surface of the metal structure.

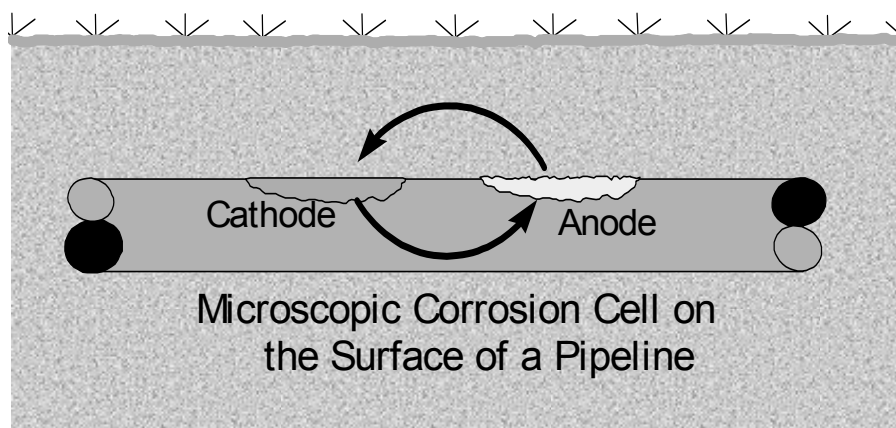


Figure 2.1 Microscopic Corrosion Cell

The concept of cathodic protection (CP) involves reducing the potential difference between the local anodic and cathodic sites to zero, resulting in zero corrosion current flow. This can be accomplished by impressing current onto the structure from an external electrode and polarizing the cathodic sites in an electronegative direction. As the potentials of the cathodic sites polarize toward the potentials of the anodic sites, corrosion current is reduced. When the potentials of all cathodic sites reach the open circuit potential of the most active anodic sites, corrosion is eliminated on the structure. The structure is now the cathode of an intentional macroscopic corrosion cell.

Corrosion of the metal will cease once the applied cathodic protection current equals or exceeds the corrosion current.

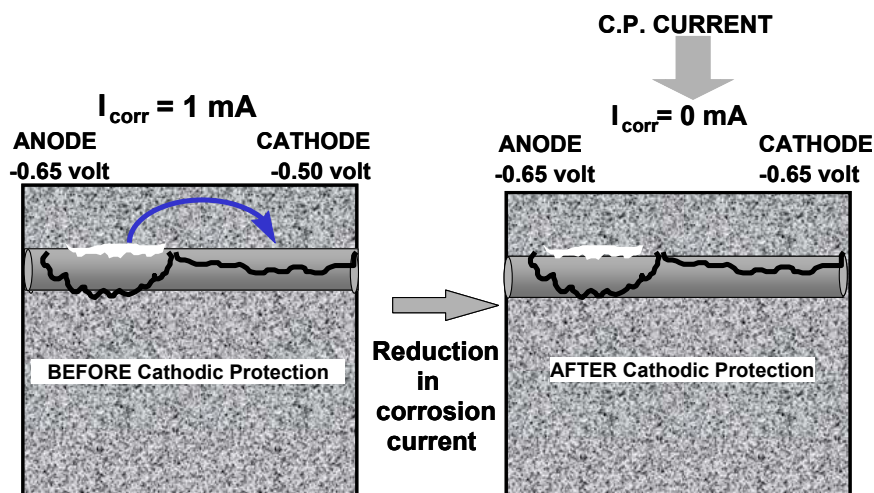


Figure 2.2 Cathodic Protection Applied to a Structure

Cathodic protection current is impressed from an external cathodic protection anode through the electrolyte to the metal and reduces the potential difference between anodic and cathodic sites (see Figure 2.2).

Polarization of a Structure

Cathodic protection is a polarization phenomenon and polarization is a change in potential caused by current. When current goes from the electrolyte to the metal, a reduction reaction occurs. Products from these reactions change the chemical composition of the electrolyte at the structure/electrolyte interface. The chemistry difference at the interface, as measured by the structure potential, is referred to as *polarization*. When cathodic protection current is interrupted, the polarization will dissipate similarly to the voltage dissipation of a capacitor but may never reach the original native potential depending on the reaction products.

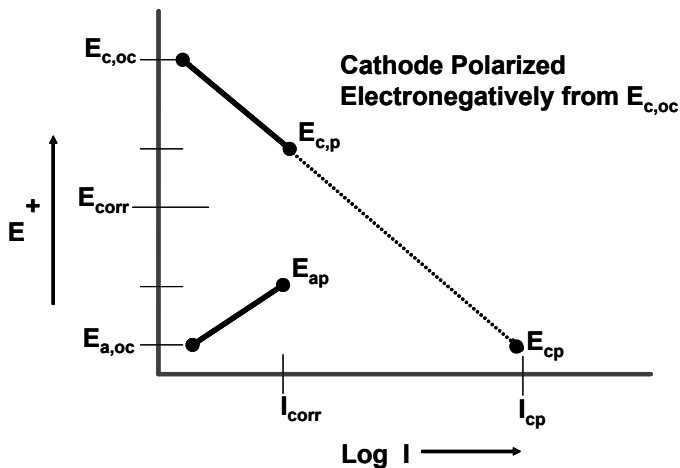


Figure 2.3 Polarization of a Structure

As a structure polarizes, its potential changes in an electronegative direction (see Figure 2.3). Polarization occurs in a step-like manner with the more positive or cathodic sites polarizing first. As the potential of the first cathodic sites equals the potential of other sites, polarization begins at other sites. A simplified description is given in Figure 2.4.

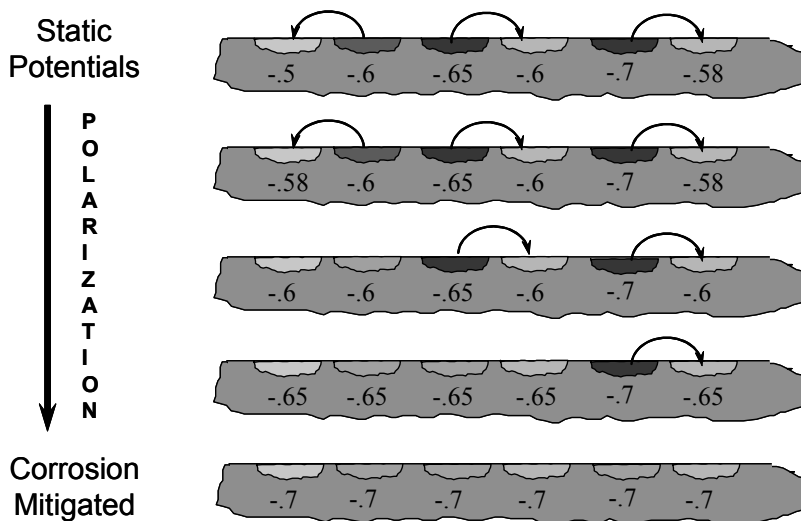
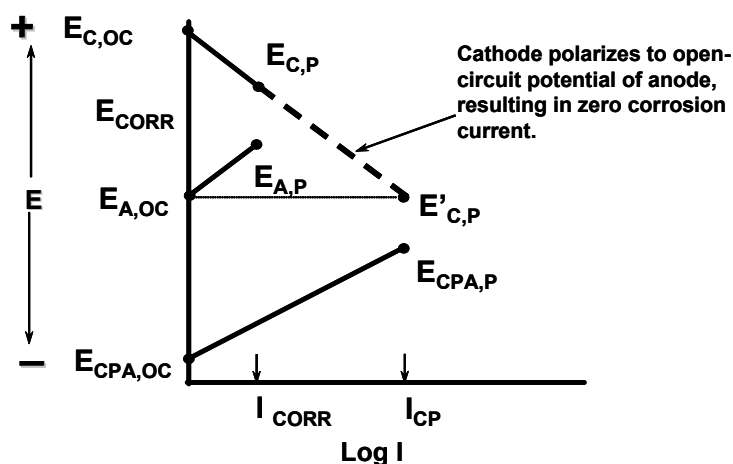


Figure 2.4 Polarization of a Structure

To mitigate corrosion, all existing cathode sites must be electronegatively polarized to a potential equal to the open circuit potential of the most active anode potential existing on the structure. Polarization of a structure is accomplished by applying external current, the magnitude of which depends on the cathodic polarization behavior. Discussed later in this chapter are factors that affect current requirements for adequate cathodic protection of a structure. Figure 2.5 represents the polarization of the cathode to the open circuit potential of the anode of a corrosion cell on a structure using cathodic protection.



where:

- $E_{C,OC}$ = Structure cathode potential, open circuit, corrosion cell not active
- $E_{A,OC}$ = Structure anode potential, open circuit, corrosion cell not active
- $E_{C,P}$ = Structure cathode potential, corrosion cell active, before CP applied
- $E_{A,P}$ = Structure anode potential, corrosion cell active, before CP applied
- E_{CORR} = Corrosion potential with structure anode and structure cathode connected
- I_{CORR} = Corrosion current before CP applied
- $E_{CPA,OC}$ = CP anode potential, no CP current
- $E'_{C,P}$ = Structure cathode potential with CP current applied
- $E_{CPA,P}$ = CP anode potential, CP current flowing
- I_{CP} = Cathodic protection current between CP anode and structure

Figure 2.5 Cathode Polarized to the Open Circuit Potential of the Anode

Polarization of the cathodes to the open circuit potential of the anodes is the true criterion for eliminating corrosion. However, for all practical purposes, it is impossible to determine the open circuit potential of the most active anodic site. Because corrosion cells are usually microscopic and the measured potentials are corrosion potentials (E_{CORR}), the initial measurements are most likely to be an average of corrosion potentials for several corrosion cells. Therefore, several surrogate criteria, which we will discuss later in this chapter, were developed to assist meeting the true criterion.

Current Requirement

The amount of current required to provide adequate protection depends on the surface area to be protected and the polarization behavior of the structure in its environment.

Surface Area

Current requirement is directly proportional to the exposed metal surface area to the electrolyte. For example, a coated structure requires less current than a bare structure. A coated structure needs protective current only at coating

defects (holidays). To consider an actual example, let us look at the following calculations.

Example

What is the current required to protect an uncoated 30.48 cm (12 in.) diameter steel pipeline 1,524 m (5,000 ft) in length that is buried in soil with a resistivity of 10,000 Ω -cm? Assume experience has shown that adequate levels of cathodic protection can be achieved from 10.76 mA/m² (1 mA/ft²) of bare surface area. Compare this with the current required to protect the same pipeline if it is coated.

Bare Example:

$$I_p(\text{given}) = (10.76 \text{ mA/m}^2) 1.0 \text{ mA/ft}^2$$

Metric:

Total Surface Area =

$$\pi dL = \pi \times \frac{30.48 \text{ cm}}{100 \text{ cm/m}} \times 1524 \text{ m} = \pi \times 0.03048 \times 1524 = 1459.3 \text{ m}^2$$

$$= \pi \times 0.03048 \times 1524$$

$$= 1459.3 \text{ m}^2$$

$$\text{Total Surface Area} = 15,708 \text{ ft}^2 (1,459 \text{ m}^2)$$

$$\therefore I_{\text{req'd}} = 10.76 \text{ mA/m}^2 \times 1459 \text{ m}^2 = 15.7 \text{ A}$$

Imperial:

$$\text{Total Surface Area} = \pi dL = \pi \times (12 \text{ in} \times 1 \text{ ft}/12 \text{ in}) \times 5000 \text{ ft}$$

$$= \pi \times 1 \text{ ft} \times 5000 \text{ ft}^2$$

$$\text{Total Surface Area} = 15,708 \text{ ft}^2$$

$$\therefore I_{\text{req'd}} = 1.0 \text{ mA/ft}^2 \times 15,708 \text{ ft}^2 = 15,708 \text{ mA} = 15.7 \text{ A}$$

Coated Example:

Assume that 5 percent of the pipe contains holidays or defects in the coating. Then:

Metric:

$$\begin{aligned} \text{Surface Area of portion of Coated Pipe that is bare} \\ = 0.05 \times 1459 \text{ m}^2 = 73 \text{ m}^2 \end{aligned}$$

$$\therefore I_{\text{req'd}} = 10.76 \text{ mA/m}^2 \times 73 \text{ m}^2 = 785 \text{ mA} = 0.785 \text{ A}$$

Imperial:

$$\begin{aligned} \text{Surface Area of portion of Coated Pipe that is bare} \\ = 0.05 \times 15,708 \text{ ft}^2 = 785 \text{ ft}^2 \end{aligned}$$

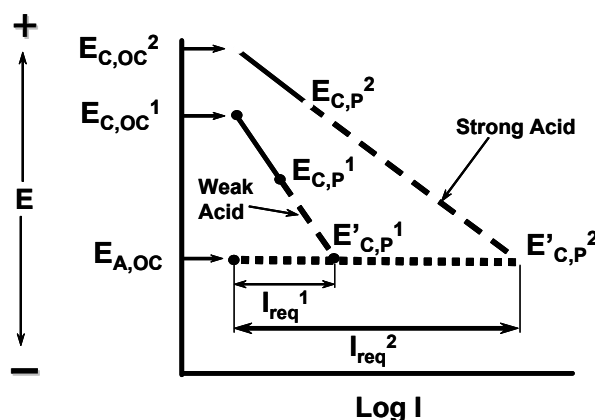
$$\therefore I_{\text{req'd}} = 1.0 \text{ mA/ft}^2 \times 785 \text{ ft}^2 = 785 \text{ mA} = 0.785 \text{ A}$$

Polarization

Factors that affect polarization, which in turn affect corrosion current have been discussed. In the case of a corrosion cell, an increase in polarization is desired whether it is anodic, cathodic, or both, because it decreases corrosion current. For a cathodic protection system, an increase in the cathodic polarization is desired to decrease the current requirement for the structure. However, cathodic protection anodes are designed to have minimal anodic polarization to increase current output.

Effect of Environment pH on CP Current Requirement

The current required for cathodic protection generally is greater in low pH (acids) than in high pH (basic) and neutral environments. Two phenomena account for this increase: (1) a shift in the positive direction of the structure's open circuit cathode potential, and (2) a flattening of the cathodic polarization curve for the structure, as indicated in Figure 2.6.

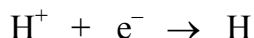


where:

- $E_{C,OC}^2$ = Cathode potential, strong acid solution, no corrosion
- $E_{C,OC}^1$ = Cathode potential, weak acid, no corrosion
- $E_{A,OC}$ = Anode potential
- $E_{C,P}^2$ = Cathode potential, strong acid, corroding
- $E_{C,P}^1$ = Cathode potential, weak acid, corroding
- $E'_{C,P}^1$ = CP potential required, weak acid
- $E'_{C,P}^2$ = CP potential required, strong acid
- I_{req}^1 = CP current needed for weak acid
- I_{req}^2 = CP current required for strong acid

Figure 2.6 Effect of Environment pH on Current Required for Protection

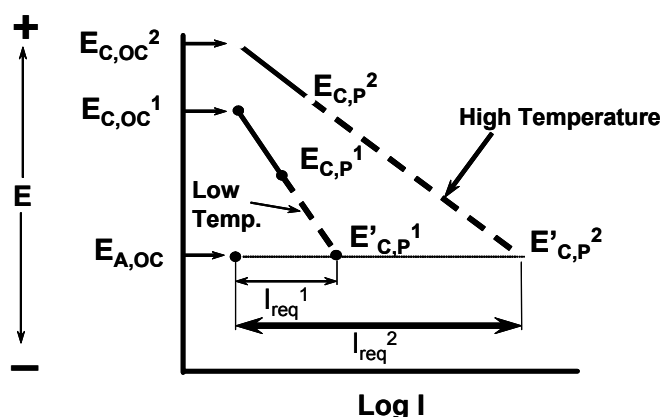
The structure's cathodic polarization slope is flattened with increasing acidity because of the increased concentration of reducible hydrogen ion (H^+) according to the reaction:



The pH of an electrolyte (soil or water) is rarely a neutral 7. This results from the presence of various ionic species in the electrolyte as a result of the hydrolysis of salts (e.g., sodium carbonate, ammonium sulfate, and others). Depending on the nature of the salt, the pH can shift in either the acidic or basic direction. For example, ammonium sulfate (an acid salt) used as a fertilizer tends to decrease pH of the soil.

Temperature Effect on CP Current Requirement

Increased temperature has a depolarizing effect because of the increased rate of diffusion of reducible species to the cathodic sites, a decrease in concentration polarization. Accordingly, the rate of the reduction reaction is increased, thus decreasing the level of polarization and increasing the cathodic protection current requirement, as illustrated in Figure 2.7.



where:

$E_{C,OC}^2$	=	Cathode potential, high temperature, no corrosion
$E_{C,OC}^1$	=	Cathode potential, low temperature, no corrosion
$E_{A,OC}$	=	Anode potential
$E_{C,P}^2$	=	Cathode potential, high temperature, corroding
$E_{C,P}^1$	=	Cathode potential, low temperature, corroding
$E'_{C,P}^1$	=	CP potential required, low temperature
$E'_{C,P}^2$	=	CP potential required, high temperature
I_{req}^1	=	CP current needed for low temperature
I_{req}^2	=	CP current required for high temperature

Figure 2.7 *Effect of Temperature on Current Required for Cathodic Protection*

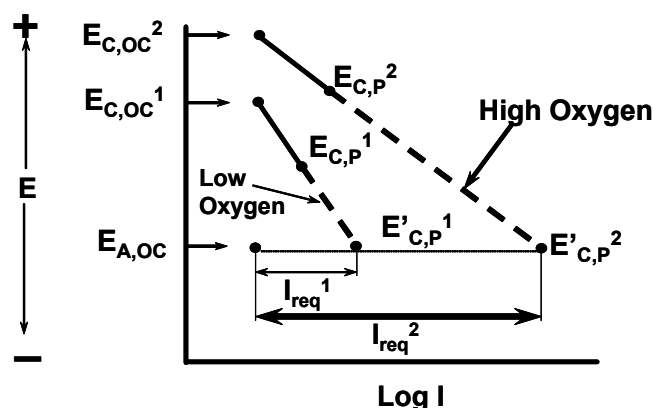
Also, increased temperature will increase ionization. As ionization increases, the electrolyte's conductivity increases, which increases corrosion current and the amount of cathodic protection current required for adequate protection. Activation polarization decreases because the electrochemical reactions speed up.

Effect of Oxidizers on CP Current Requirement

Oxygen or other oxidizers increase the current requirements as a result of flattening the cathodic polarization slope. Oxygen, for instance, participates in the cathodic reduction reaction:



thereby reducing polarization. Figure 2.8 illustrates this effect.



where:

$E_{C,OC}^2$ = Cathode potential, high oxygen, no corrosion

$E_{C,OC}^1$ = Cathode potential, low oxygen, no corrosion

$E_{A,OC}$ = Anode potential

$E_{C,P}^2$ = Cathode potential, high oxygen, corroding

$E_{C,P}^1$ = Cathode potential, low oxygen, corroding

$E'_{C,P}^1$ = CP potential required, low oxygen

$E'_{C,P}^2$ = CP potential required, high oxygen

$I_{req,d}^1$ = CP current needed for low oxygen

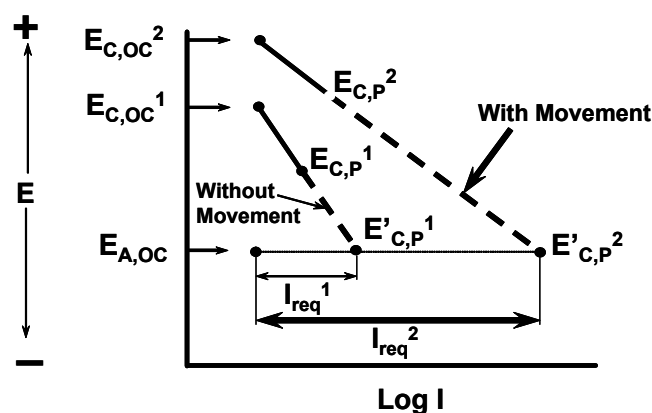
$I_{req,d}^2$ = CP current required for high oxygen

Figure 2.8 Effect of Oxygen on Current Required for Cathodic Protection

Accordingly, structures in well aerated soils, such as sand and gravel, require more cathodic protection current than structures surrounded by relatively deaerated soils, such as clay.

Effect of Relative Movement Between the Structure and Electrolyte on CP Current Requirements

An increase in the relative movement between the electrolyte and the structure causes an increase in current requirement. This is due primarily to the increased availability of reducible species at the structure surface and the resulting increase in the rate of the reduction reaction. This effect, illustrated in Figure 2.9, is exhibited on such structures as ships and their propellers, docks exposed to water flow or tides, offshore structures, and internal surfaces of condenser water boxes.



where:

$E_{C,OC}^2$ = Cathode potential, with movement, no corrosion

$E_{C,OC}^1$ = Cathode potential, no movement, no corrosion

$E_{A,OC}$ = Anode potential

$E_{C,P}^2$ = Cathode potential, with movement, corroding

$E_{C,P}^1$ = Cathode potential, no movement, corroding

$E'_{C,P}^1$ = CP potential required, no movement

$E'_{C,P}^2$ = CP potential required, with movement

I_{req}^1 = CP current needed for no movement

I_{req}^2 = CP current required for with movement

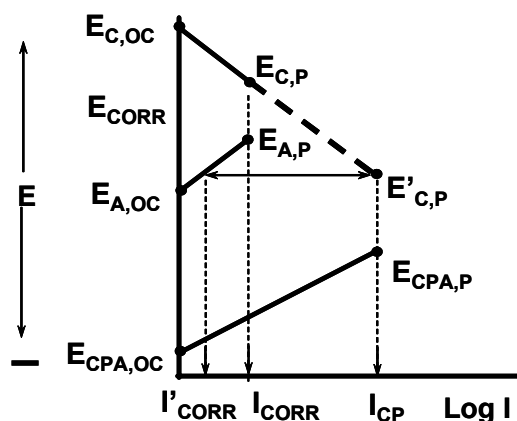
Figure 2.9 Effect of Relative Movement on Current Required for Cathodic Protection

The current requirements, however, are not necessarily a linear function of the fluid velocity. If the fluid flow is laminar, opposed to turbulent, then the requirements are lower.

For instance, a ship under way requires more cathodic protection current than a ship at rest; similarly, the stern of a ship requires more current than the bow.

Applied Current vs. Corrosion Rate

If all cathodes are not sufficiently polarized in the electronegative direction, then a residual corrosion current (I_{CORR}) will remain and some corrosion will continue to take place. See Figure 2.10.



where:

- $E_{C,OC}$ = Structure cathode potential, open circuit, corrosion cell not active
- $E_{A,OC}$ = Structure anode potential, open circuit, corrosion cell not active
- $E_{C,P}$ = Structure cathode potential, corrosion cell active, before CP applied
- $E_{A,P}$ = Structure anode potential, corrosion cell active, before CP applied
- E_{CORR} = Corrosion potential with structure anode and structure cathode connected
- I_{CORR} = Corrosion current before CP applied
- $E_{CPA,OC}$ = CP anode potential, no CP current
- $E'_{C,P}$ = Structure cathode potential with CP current applied [not quite at open circuit potential of anode ($E_{A,OC}$)]
- $E_{CPA,P}$ = CP anode potential, CP current flowing
- I_{CP} = Cathodic protection current between CP anode and structure
- I'_{CORR} = Corrosion current with partial CP applied

Figure 2.10 Corrosion Current Reduced by Application of Cathodic Protection Current

If the criterion for protection is not achieved, the corrosion rate is reduced nevertheless (see Figure 2.10).

To reduce the residual corrosion current to zero, cathodic protection current must be disproportionately increased. The relationship between applied cathodic protection current and corrosion rate is logarithmic. The first increment of applied cathodic protection results in the largest decrease in corrosion.

On the other hand, cathodic polarization at potentials more electronegative than the static anode potential has no benefit and, in extreme cases can be detrimental to the structure and/or its coating. This so called *overprotection* can be

detrimental to amphoteric metals and alloys, such as aluminum, zinc, and lead, which may corrode at high rates in both basic and acidic environments. The formation of hydroxyl ions at the cathode causes the pH of the electrolyte next to the cathode to become alkaline. This can deteriorate amphoteric metals and cause the coating to disbond from the substrate. Overprotection causing coating disbondment depends on the particular coating. For pipeline coatings, polarized potential values more negative than $-1,200 \text{ mV}_{\text{CSE}}$ should be avoided. For non-pipeline coatings, the coating manufacturer should be consulted to determine if the coating is compatible with CP. Excessive protection can result in hydrogen damage to some metals. Hydrogen embrittlement is discussed in more detail under “Environmental Cracking.”

Figure 2.11 illustrates the logarithmic relationship between cathodic protection current and corrosion rate.

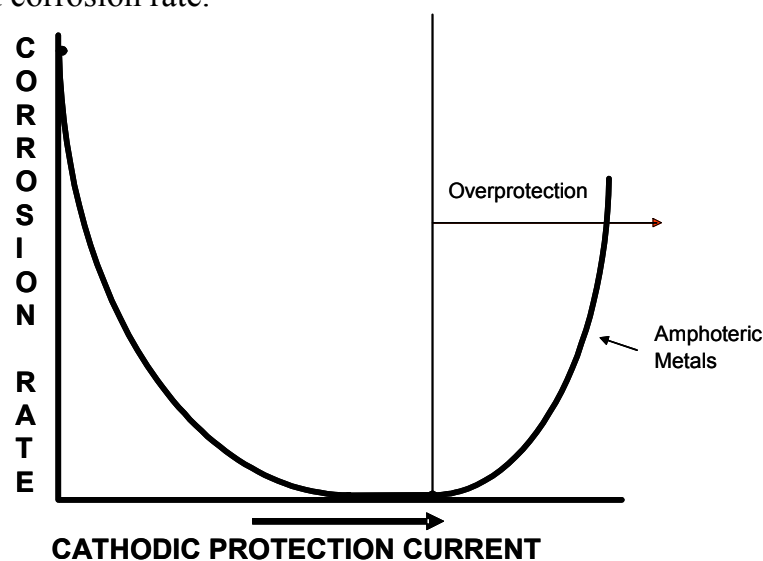


Figure 2.11 Cathodic Protection Current vs. Corrosion Rate

In some circumstances, the cost to reduce the corrosion rate to zero may not be justified. A low, rather than zero, corrosion rate may be both tolerable and acceptable in terms of minimizing total annual expenses if safety and compliance with government regulations are not jeopardized.

From a practical standpoint, how can we determine the amount of current required to mitigate corrosion on a structure in its particular environment? When all of the cathodic sites have polarized to the open circuit potential of the most active anodic site, corrosion is mitigated but we can not measure the potential of the individual anodes and cathodes. A surrogate criterion is therefore required.

Criteria for Cathodic Protection

In the Appendices section of this manual you will find NACE Standard RP0169, “Control of External Corrosion on Underground or Submerged Metallic Piping Systems.” Several criteria for determining the achievement of adequate cathodic protection are found in Section 6 of this standard, “Criteria and Other Considerations for Cathodic Protection.” Students are advised to read at least this section. These criteria were developed through laboratory experiments or were determined empirically by evaluating data from successfully operated cathodic protection systems. They may be used independently or in combination with one another.

For this course we will discuss primarily the criteria for mitigating corrosion on steel and cast iron piping. It is important to note that there are also different criteria for copper, aluminum, lead, and also steel embedded in concrete. Government regulations regarding criteria differ in different countries, and the selection of an appropriate criterion will depend on local governmental regulations.

There are three NACE criteria that apply to steel: two involve a structure-to-electrolyte potential of equal to or more negative than -850 mV in reference to a copper-copper sulfate reference electrode (CSE), and one is a polarization change of 100 mV.

Earlier in this chapter, we learned the true criterion for corrosion mitigation is polarizing the entire structure to the open circuit potential of the most active anodic site on the structure. Since the above criteria are only surrogates for the true criterion, the basis of each is important to understand for appropriate application and limitation.

RP0169 Criteria

The three criteria defined in the NACE Standard RP0169 for steel and cast iron (including ductile iron) are:

A negative (cathodic) potential of at least 850 mV with the cathodic protection applied. This potential is with respect to a saturated copper-copper sulfate reference electrode contacting the electrolyte. Voltage drops (IR drops) other than those across the structure-to-electrolyte boundary must be considered for valid interpretation of this voltage measurement. That is,

$$E_{-850} = E_{\text{on}} - IR.$$

A negative polarized potential of at least 850 mV relative to a saturated copper-copper sulfate reference electrode (Instant Off Potential).

A minimum of 100 mV of cathodic polarization between the structure surface and a stable reference electrode contacting the electrolyte. The formation or decay of polarization can be measured to satisfy this criterion.

$$\Delta E_{100} = E_{\text{OFF}} - E_{\text{DEPOLARIZED}}$$

OR

$$\Delta E_{100} = E_{\text{OFF}} - E_{\text{CORR}}$$

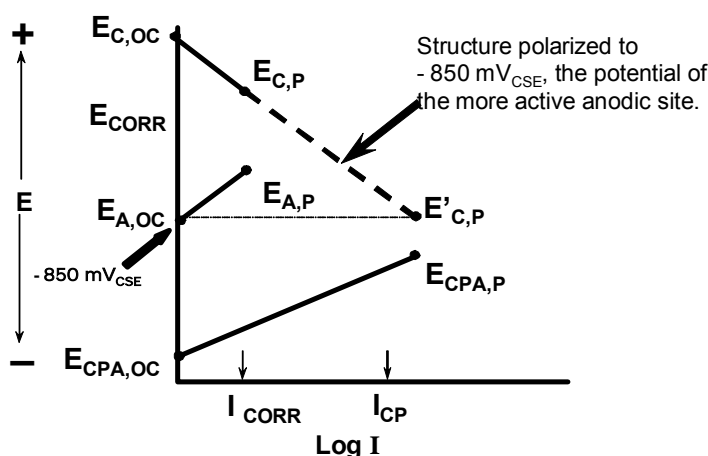
NOTE: The most recent version of NACE or any standard must be referenced in order to obtain the most recent criteria and information regarding the application of that criteria.

Basis of RP0169 Criteria

–850 mV_{CSE} Potential for Steel

For any metal, its energy level is highest when it is new or “bright and shiny.” Laboratory measurements of new steel samples in many different soil environments have indicated the most active corrosion potential is between –800 mV and –850 mV both referenced to a saturated copper-copper sulfate reference electrode (CSE). Therefore, polarizing a steel structure to –850 mV_{CSE} would satisfy the true criterion based on the most active anodic site being –850 mV_{CSE}. If the most active corrosion potential is less negative than –850 mV_{CSE} for a given steel structure, then this criterion is conservative in mitigating corrosion, as shown in Figure 2.12.

The –850 mV_{CSE} polarization potential is further supported by long term laboratory application of this value to test coupons. It is generally agreed that this criterion reduces corrosion to approximately one (1) mil/year [0.0254 mm/yr]. The –850 mV_{CSE} potential is the basis for the first two criteria. The difference between the two criteria will be discussed later in the IR Drop section.



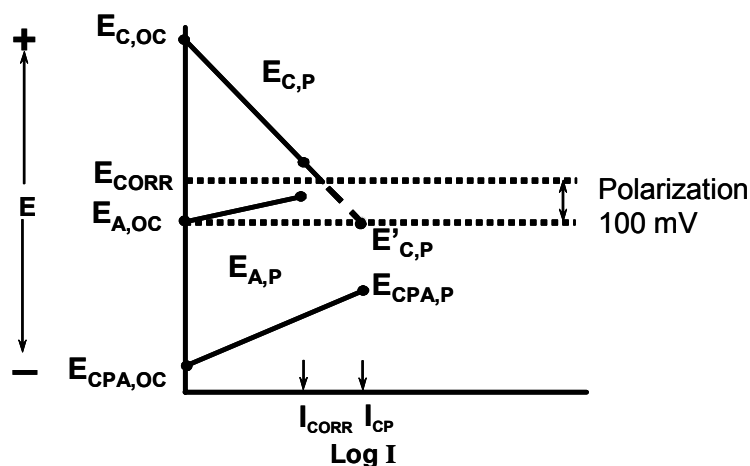
where:

- $E_{C,OC}$ = Structure cathode potential, open circuit, corrosion cell not active
- $E_{A,OC}$ = Structure anode potential, open circuit, corrosion cell not active
- $E_{C,P}$ = Structure cathode potential, corrosion cell active, before CP applied
- $E_{A,P}$ = Structure anode potential, corrosion cell active, before CP applied
- E_{CORR} = Corrosion potential with structure anode and structure cathode connected
- I_{CORR} = Corrosion current before CP applied
- $E_{CPA,OC}$ = CP anode potential, no CP current
- $E'_{C,P}$ = Structure cathode potential with CP current applied
- $E_{CPA,P}$ = CP anode potential, CP current flowing
- I_{CP} = Cathodic protection current between CP anode and structure

Figure 2.12 Structure polarized to -850 mV_{CSE}

100 mV Polarization

Although polarization of a steel structure to -850 mV_{CSE} provides adequate cathodic protection, it may be too conservative or too costly for older structures. For older structures, the most active anodic site can be significantly more noble than -850 mV_{CSE} . Consequently, the mixed or corrosion potential (E_{CORR}) is more noble on older structures. From laboratory experiments and data obtained from successfully operating cathodic protection systems, it has been determined that a minimum of 100 mV of polarization on a structure should provide adequate cathodic protection. Figure 2.13 illustrates this situation where the structure is polarized to a point ($E'_{C,P}$) that is 100 mV more active than E_{CORR} . While there can still be some corrosion occurring and shown by the point I'_{CORR} , the reduction in corrosion can be significant. (Keep in mind that the scale is logarithmic.) The 100 mV criterion is also applicable for metals other than steel and with reference cells other than copper-copper sulfate.



where:

- $E_{C,OC}$ = Structure cathode potential, open circuit, corrosion cell not active
- $E_{A,OC}$ = Structure anode potential, open circuit, corrosion cell not active
- $E_{C,P}$ = Structure cathode potential, corrosion cell active, before CP applied
- $E_{A,P}$ = Structure anode potential, corrosion cell active, before CP applied
- E_{CORR} = Corrosion potential with structure anode and structure cathode connected
- I_{CORR} = Corrosion current before CP applied
- $E_{CPA,OC}$ = CP anode potential, no CP current
- $E'_{C,P}$ = Structure cathode potential with CP current applied (100 mV polarization)
- $E_{CPA,P}$ = CP anode potential, CP current flowing
- I_{CP} = Cathodic protection current between CP anode and structure
- I'_{CORR} = Corrosion current with 100 mV CP applied

Figure 2.13 Polarization of 100 mV

Polarized Potential

Since cathodic protection is a polarization phenomenon, the polarized potential of a structure must be measured to determine the level of protection it is receiving. The following is the definition of a polarized potential:

The potential across the structure/electrolyte interface that is the sum of the corrosion potential and the cathodic polarization.

The potential of interest when determining adequate cathodic protection is the polarized potential across the structure/electrolyte interface (see Figure 2.14).

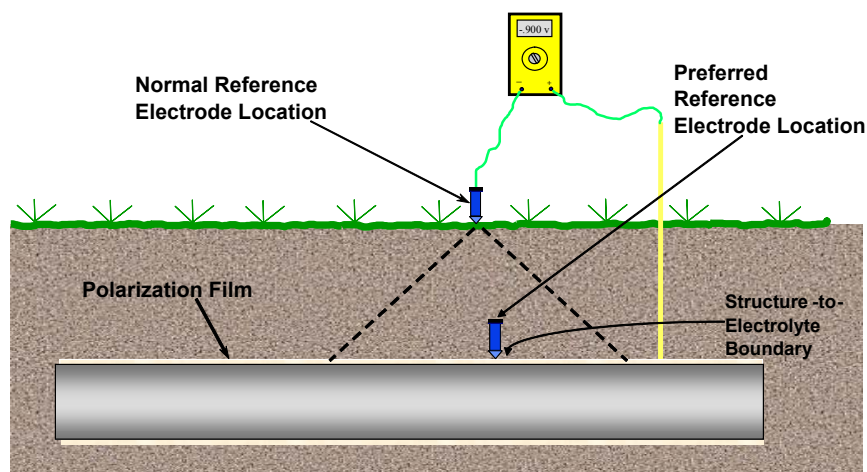
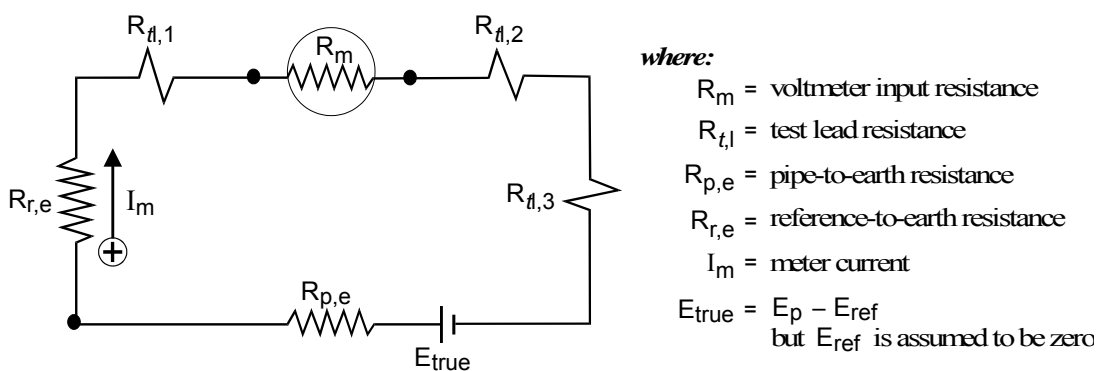


Figure 2.14 Measuring Surface Structure-to-Electrolyte Potential

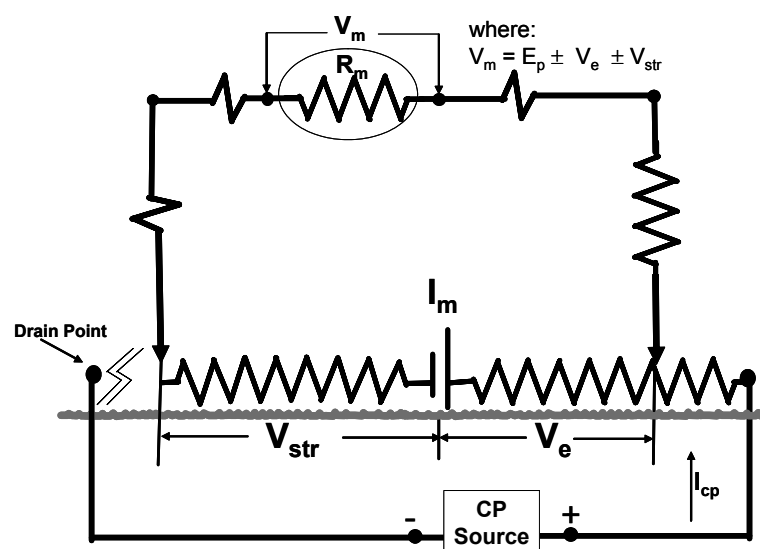
The metering circuit can be shown by the two electrical schematics in Figures 2.15(a) and 2.15(b).



where:

$$V_m = \frac{R_m}{R_t} \times E_{true}$$

Figure 2.15(a) Electrical Schematic of the Structure-to-Electrolyte Measurement Circuit



V_e = voltage drop in earth between reference and structure
 V_{str} = voltage drop in structure between point of contact and location of reference

$$\text{where : } V_m = E_p \pm V_e \pm V_{str}$$

Figure 2.15(b) Electrical Schematic Illustrating Voltage Drops External to the Meter Circuit

However, when a potential is measured, the result is the algebraic sum of all the voltage drops in the measuring circuit, as shown in Figure 2.15.

For a measured potential to represent the polarized potential across the structure/electrolyte interface, all other voltage drops in the measuring circuit must be negligible. Since voltage (or IR drop) is a product of current and resistance, voltage decreases when either current or resistance decreases. Current usually refers to the applied cathodic protection current; however, the measurement current or stray currents can be significant. The measurement circuit current is small if the input resistance of the meter is large. Voltage drops are negligible in the measuring circuit under the following conditions:

Metallic paths — when lengths are short and/or area cross-sectional to current flow is large.

Contact between reference cell and electrolyte — when moist and/or large area contact is made.

Connection points — when good metal/metal contacts are made.

Internal circuit of the meter — when a high-input impedance meter is used.

Electrolyte — when resistivity and/or cathodic protection current density are low.

All the voltage drops in the measuring circuit are controllable except for the one across the electrolyte. The IR drop across the electrolyte can be reduced to near zero by placing the reference electrode near the structure coating holiday or by interrupting the current flow.

In addition to attempting to make the IR drop negligible, another approach is to determine the magnitude of the IR drop either through measurement or calculations and adjust the measured potential by subtracting the IR drop.

Application of Criteria

The first criterion for steel, a potential of $-850 \text{ mV}_{\text{CSE}}$ obtained with current applied, is based on negligible IR drop or eliminating the IR drop from the measurement. Consideration should be given to the specific structure and its environment in determining if IR drop is negligible prior to employing this criterion. The IR drop is usually negligible when the current density and/or the resistivity are low.

The second criterion, a polarized potential of $-850 \text{ mV}_{\text{CSE}}$, is based on eliminating IR drop during the measurement. Either removing the resistance (electrolyte) or the current can eliminate IR drop. If the potential is measured at the structure/electrolyte interface, then the electrolyte is no longer in the measuring circuit and resistance is zero. If cathodic protection current is interrupted, then current is zero. Remember that polarization will dissipate when current is interrupted, and polarization is the measurement of interest. Therefore, when current is interrupted, the potential should be measured at “instant off,” which refers to the potential after IR drop is eliminated but before polarization begins to dissipate.

The 100 mV polarization criterion can be applied by either starting with the known corrosion potential or the polarized structure potential, or determining the other. In fact, the criterion is based on the difference between these two potentials. Of course, the IR drop must be eliminated from the measured “on” potential to determine the polarized potential. In practice, for a structure not cathodically protected, the measurement technique may involve measuring the corrosion potential first. Then, current is applied until the structure is polarized. Current is then interrupted momentarily in order to measure the polarized potential.

A technique used to evaluate a structure that is receiving cathodic protection begins with momentary interruption of the current to determine the polarized potential. Then, with the CP current remaining off, dissipation of the polarized potential is monitored. When no further potential change is evident over time or the desired depolarization has occurred, then the potential is referred to as the depolarized corrosion potential of the structure. Figure 2.16 illustrates a depolarization measurement.

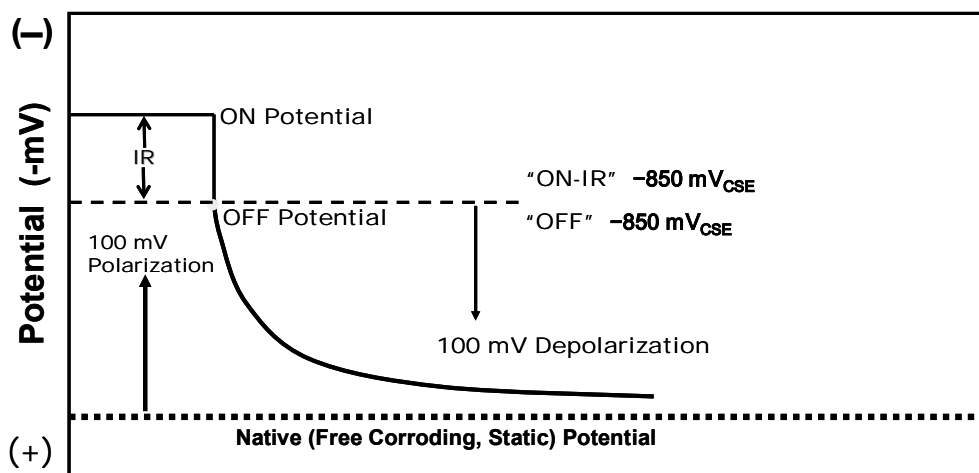


Figure 2.16 Example of a Depolarization Curve

Ineffective or partial protection may be the result of abnormal conditions. Such conditions may include elevated temperatures, disbonded coatings, electrical shielding, bacterial attack, and unusual contaminants in the electrolyte.

Other Criteria

Aluminum

The criterion for cathodically protecting aluminum based on NACE Standard RP0169 is a minimum of 100 mV of polarization as measured between the structure surface and a stable reference electrode contacting the electrolyte.

Aluminum is amphoteric. That is, the metal corrodes under both acid and alkaline conditions. The polarized potential should not be more negative than $-1,200 \text{ mV}_{\text{CSE}}$ measured between the pipe surface and a saturated copper-copper sulfate reference electrode to prevent a buildup of alkali on the surface that could *increase* the corrosion rate. Likewise, if the pH of the environment is above 8.0, the conditions should be re-evaluated before cathodic protection is applied. Amphoteric metals should be isolated from all other metal in the system and protected separately.

Copper

The criteria for the cathodic protection of copper based on NACE Standard RP0169 is a minimum of 100 mV of polarization as measured between the structure surface and a stable reference electrode contacting the electrolyte.

In the case of dissimilar metal piping, a negative voltage between all pipe surfaces and a stable reference electrode equal to that required for the protection of the most anodic metal is required.

Reinforced Concrete Structures

NACE Standard RP0290, “Cathodic Protection of Reinforcing Steel in Atmospherically Exposed Structures,” specifies two criteria for steel reinforcement embedded in concrete. One criterion is that the structure exhibits a 100 mV polarization development or 100 mV polarization decay after disconnecting or turning off the CP current.

A second criterion is that the polarized potential be at least as negative as the potential at the base of the Tafel Slope on an E-Log I curve. The E-Log I test is performed by incrementally increasing the cathodic protection current from the installed system. At each interval, the IR drop free potential of the steel reinforcement is measured relative to a stable reference electrode. The plot of potential vs. applied current is called an E-Log I plot. The straight line portion of the plot is called the Tafel Slope and corresponds to line $E_{C,P}-E'_{C,P}$ in Figure 2.24. The structure-to-reference electrode potential at the base of the Tafel Slope will be above point E_{CORR} , and at this point, the amount of corrosion should be significantly reduced (although not completely stopped).

A third criterion in this standard is that the polarized potential is statistically more negative than the statistical standard deviation of the native potentials.

Other NACE International Recommended Practices

NACE Standard RP0285, “Corrosion Control of Underground Storage Tank Systems by Cathodic Protection.” Criteria are the same as NACE Standard RP0169.

NACE Standard RP0388, “Impressed Current Cathodic Protection of Internal Submerged Surfaces of Steel Water Storage Tanks.” The criteria defined in this standard are as follows: (1) –850 mV vs. a copper-copper sulfate electrode or (2) a minimum 100 mV of polarization between the tank surface and a stable reference electrode contacting the electrolyte (the formation or decay of

polarization can be measured to satisfy this criterion). The 100 mV criterion is only applicable to steel water tanks not having corrosion cells caused by connection to more noble metals such as copper, brass or passive stainless steel. There is also a caution about possible coating damage at potentials above $-1,100$ mV.

NACE Standard RP0169 “Control of External Corrosion on Underground or Submerged Metallic Piping Systems.” The three criteria defined in this standard are as follows:

- 1) -850 mV applied vs. a copper-copper sulfate reference electrode, after IR drop is considered
- 2) -850 mV polarized vs. a copper-copper sulfate reference electrode,
- 3) minimum of 100 mV polarization between the structure surface and a stable reference electrode. The formation or decay of polarization can be measured to satisfy this criterion.

NACE Standard RP0196 “Galvanic Anode Cathodic Protection of Internal Submerged Surfaces of Steel Water Storage Tanks.” This standard uses the -850 mV_{CSE} applied and the -850 mV_{CSE} polarized potential criteria found in NACE Standard RP0169.

NACE Standard RP0575 “Internal Cathodic Protection Systems in Oil-Treating Vessels.” This standard also uses a criterion of -850 mV to a copper sulfate reference electrode for steel vessels. The criterion changes to -950 mV_{CSE} if sulfides are present in the fluid. It also specifies a current density of 10 mA/ft^2 (110 mA/m^2) as an alternative criterion. The leak history is also a criterion.

NACE Standard RP0180 “Cathodic Protection of Pulp and Paper Mill Effluent Clarifiers.” This practice uses the NACE Standard RP0169 criteria. In addition, the practice defines protection as polarizing the entire surface to the potential of the most active anode.

NACE Standard RP0193 “External Cathodic Protection of On-Grade Metallic Storage Tank Bottoms.” This standard uses the same criterion as those found in NACE Standard RP0169 measured at the tank periphery, center, and in between. The potential at the periphery will not necessarily reflect potentials in the center of the tank when anodes are around the outside ring.

NACE Standard RP0194 “Criteria and Test Methods for Cathodic Protection.” This standard applies to lead cable. The listed criteria are:

- $-700 \text{ mV}_{\text{CSE}}$ for bare lead, jute, thermoplastic, or polyethylene jacketed cable
- $-850 \text{ mV}_{\text{CSE}}$ for steel tape or galvanized wire wrapped cable
- 250 mV change from open circuit potential
- 100 mV polarization

Note that lead is an amphoteric metal.

International Standard ISO 15589-1

Petroleum and Natural Gas Industries—Cathodic Protection of Pipeline Transportation Systems

Part 1 On-land pipelines

- Metal-to-electrolyte potential chosen for a corrosion rate less than 0.01 mm/yr (0.39 mils/yr)
- Polarized potential more negative than $-850 \text{ mV}_{\text{CSE}}$
- Limiting critical potential not more negative than $-1,200 \text{ mV}_{\text{CSE}}$
- Anaerobic soils or sulfate-reducing bacteria (SRB) more negative than $-950 \text{ mV}_{\text{CSE}}$
- High soil resistivity
 - $-750 \text{ mV}_{\text{CSE}}$ for $100 \text{ m} < \rho < 1,000 \text{ } \Omega\text{-m}$
 - $-650 \text{ mV}_{\text{CSE}}$ for $\rho > 1,000 \text{ } \Omega\text{-m}$
- Cathodic polarization of 100 mV

Precautions:

Avoid using 100 mV under conditions of high temperatures, SRB, interference current, equalizing current, telluric current, mixed metals or SCC conditions more positive than $-850 \text{ mV}_{\text{CSE}}$.

American Water Works Association (AWWA)

D104 “Automatically Controlled, Impressed Current Cathodic Protection for the Interior of Steel Water Tanks.” This standard specifies a criterion of $-850 \text{ mV}_{\text{CSE}}$ to $-1,050 \text{ mV}_{\text{CSE}}$ polarized potential.

Non-NACE International Criteria

American Petroleum Institute (API)

API Recommended Practice 651 “Cathodic Protection of Aboveground Petroleum Storage Tanks.” Refers to NACE Standard RP0169 for external cathodic protection and NACE Standards RP0575 and RP0388 for internal cathodic protection. The standard does provide additional information.

API Recommended Practice 1632 “Cathodic Protection of Underground Petroleum Storage Tanks and Piping Systems.” Criteria are similar to NACE Standard RP0285.

Saudi Aramco Engineering Standards (SAES-X-400)

- Pipelines: $-1,200$ mV minimum and $-3,000$ mV maximum to CSE with the current ON
- Valves and Compressor piping: $-1,000$ mV min. and $-3,000$ mV max. to CSE with the current ON
- Pipeline junctions, pump stations, compressor stations: $-1,050$ mV min. and $-3,000$ mV max. to CSE with the current ON

Petroleum Development of Oman (PDO-65-12)

- -850 mV min. to CSE instant-off. Avoid potentials more negative than $-1,200$ mV CSE (off)

Abu Dhabi National Oil Company (ADNOC)

Steel in soil:	-950 to $-1,150$ mV instant off CSE -900 to $-1,100$ mV instant off SSC
Steel in concrete:	-700 to $-1,100$ mV instant off CSE -650 to $-1,050$ mV instant off SSC
Steel in water:	-850 to $-1,050$ mV instant off CSE -800 to $-1,000$ mV instant off SSC

Canada

CSA Standard Z662, “Oil and Gas Pipeline Systems,” references CGA Recommended Practice OCC-1, “For the Control of External Corrosion on

Buried or Submerged Metallic Piping Systems,” for criteria and methods. The criteria are the same as in the NACE Recommended Practice except for a condition when using the 100 mV criterion. The polarized potential must be more negative than -770 mV if SCC is suspected.

CSA Standard Z169 covers cathodic protection of aluminum.

Australia

Australia Standards Institute Standard No. 2832. This standard has three parts – Part 1 is concerned with pipes, cables and ducts, the subject of Part 2 is compact buried structures, and the topic of Part 3 is fixed immersed structures. The criteria listed are the same as NACE Standard RP0169.

Japan

Corrosion Protection and Repair Manual for Port and Harbor Steel Structures, The Overseas Coastal Area Development Institute of Japan. This document lists the criteria for the cathodic protection of steel in seawater as:

- 770 mV vs. saturated calomel electrode
- 780 mV vs. silver-silver chloride
- 850 mV vs. copper-copper sulfate reference

The document further lists the protective current density as:

	Clean areas, mA/m²	Polluted areas, mA/m²
Seawater	100	130 to 150
Sea rubble	50	65 to 75
Sea mud	20	30
Soil	10	10

Japanese Port Authority Association, Part 1, *Harbor Facility Technology Criteria and Discussion*. This document lists the same criteria and current requirements are listed above.

Japanese Water Piping Association, *Cathodic Protection Manual for Coated Steel Water Pipe*, WSP-050. This document lists the criterion as -850 mV to a copper-copper sulfate reference cell

E log I

To use the E log I technique to determine a criterion, a cathodic polarization curve for the structure must be constructed. Data for the curve are obtained by applying test currents of increasing magnitude and measuring the structure's polarized potential at each discrete test current value.

In conducting the test, several factors are important. The time interval between measurements and the current increments should be kept as consistent as possible to eliminate distortions due to the change of polarization with time. The range of test current must be greater than the estimated current required for protection. In addition, the measured potential must be corrected for IR-drop error to obtain a polarized potential (Instant Off).

The test data are then plotted on linear and semi-logarithmic paper (Figure 2.17). The data should first be plotted on a linear scale to ensure that the plot deviates from a straight line relationship. In relatively deaerated environments, such as well casings, the polarization curve often exhibits linear (Tafel) behavior with increased test current. A straight line is then drawn tangent to the Tafel portion of the E log I curve that is beyond the break in the linear plot. From this Tafel extension a wide number of interpretations are commonly in use. The most common interpretation of the E log I curve is to select the point where the tangent to the Tafel slope breaks away from the data. The current at the break-away point is considered to be the current required to achieve complete protection. In Figure 2.17, this break occurs at a current of approximately 4 A.

Note that the first points in Figure 2.17 define a curved line. The last of the points define a straight line on the semi-log graph. The point where the curvature stops and the straight line begins represents the start of Tafel behavior indicating where most all corrosion has ceased. E_{cp} is considered as an adequate potential for cathodic protection under the E log I method.

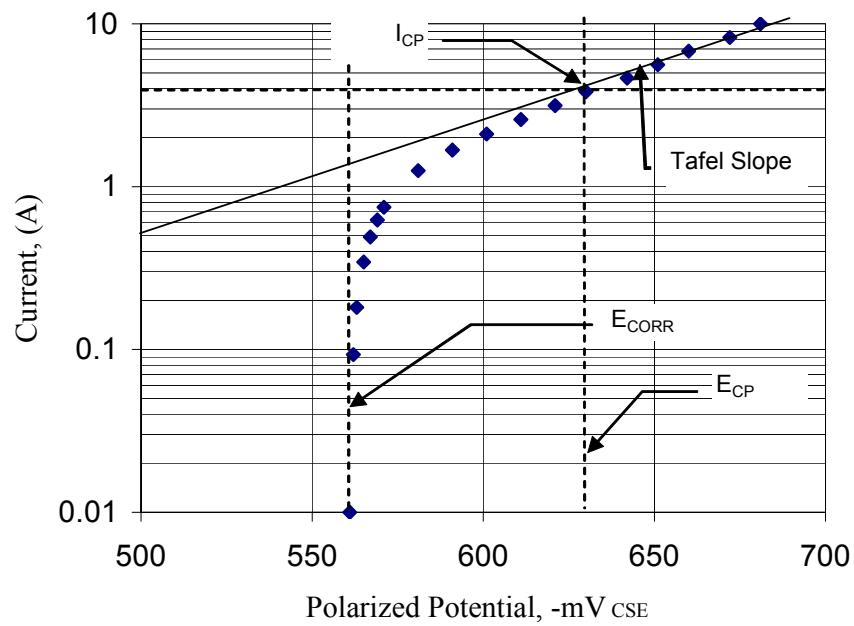


Figure 2.17 Cathodic Polarization Log I Plot

CHAPTER 3

Cathodic Protection Systems

There are 2 general types of cathodic protection systems:

- Galvanic
- Impressed Current

Components of Galvanic Cathodic Protection

There are four basic components of a galvanic anode cathodic protection system: (1) the anode, (2) the anode backfill, (3) a means of connecting the anode to the structure, (4) and the structure (see Figure 3.1).

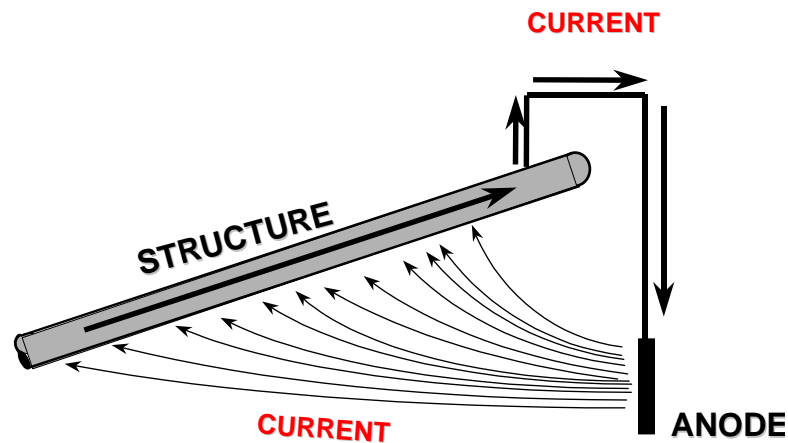


Figure 3.1 Typical Galvanic Anode Cathodic Protection

Anodes

Galvanic cathodic protection operates on the principle that a more active metal connected to a less active material will form a galvanic corrosion cell. This is used to our benefit to protect the less active metal. The more active alloy will corrode (“sacrifice” itself) to protect the protected metal; therefore, these anodes are often called *sacrificial anodes* (see Figure 3.2).

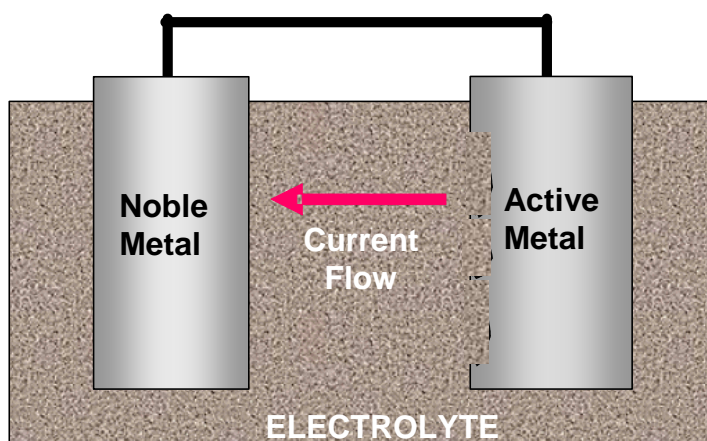


Figure 3.2 Galvanic Corrosion Cell

The practical galvanic series of metals (shown in Table 3.1) shows three metals more active than iron—magnesium, zinc, and aluminum. (Note: a complete emf series table or galvanic series table will show other metals more active than iron, but these three are the most useful.) The most common active metals used as anodes to protect iron alloys, copper, and lead are alloys of magnesium, zinc, and aluminum.

Table 3.1 Practical Galvanic Series in Seawater

Metal	Volts vs. Cu-CuSO₄	Volts vs. Ag-AgCl
	Active or Anodic End	Active or Anodic End
Magnesium	−1.60 to −1.75	−1.55 to −1.70
Zinc	−1.10	−1.05
Aluminum	−1.05	−1.00
Clean Carbon Steel	−0.50 to −0.80	−0.45 to −0.75
Rusted Carbon Steel	−0.30 to −0.50	−0.25 to −0.45
Cast/Ductile Iron	−0.50	−0.45
Lead	−0.50	−0.45
Steel in Concrete	−0.20	−0.15
Copper	−0.20	−0.15
High Silicon Iron	−0.20	−0.15
Carbon, Graphite	+0.30	+0.35
	Noble or Cathodic End	Noble or Cathodic End

Alloys of magnesium, zinc, and aluminum have been developed to enable the anode to remain active and extend the life of the anode. The pure forms of the metals are often not suitable as anodes because they undergo too much “self

corrosion” in the environment and do not stay active. Galvanic anode alloys include:

- Magnesium

Magnesium anodes are available in two alloys: a high-potential alloy having a nominal corrosion potential of -1.75 V referenced to a copper-copper sulfate electrode and a low-potential alloy having a nominal corrosion potential of -1.55 V referenced to a copper-copper sulfate electrode. Magnesium is normally used in soils and fresh water.

Standard Alloy – for use in low-resistivity soils and water

High-Potential Alloy – provides a higher driving voltage than the standard alloy.

- Zinc

Zinc anodes are also commercially available in two alloys, one for use in soils and the other for seawater applications. Zinc may undergo rapid intergranular corrosion at temperatures above 120°F (49°C). At temperatures above 130°F (54°C) and particularly in the presence of carbonates, zinc can passivate and the potential of the passive film can become more noble than steel, leading to corrosion of the steel.

MIL-A-18001 or ASTM B418 Type I – for salt water and brackish water use

ASTM B418 Type II – high purity for underground and fresh water use

- Aluminum

Aluminum alloy anodes are used primarily in seawater applications and are produced in a variety of alloys, of which the mercury and indium alloys are the most common. The indium alloy has a slightly higher corrosion potential but is less efficient than the mercury-containing alloy. Aluminum is preferred for seawater applications because it has a much lower consumption rate than magnesium or zinc. Aluminum anodes are not used in fresh water, except as impressed current anodes. They are not used underground. An alloy of aluminum-zinc and indium is used as a sacrificial anode on reinforced concrete structures. Aluminum anodes are commonly

used in process vessels containing brine. At temperatures above 120°F (49°C), however, the current output may be reduced.

Galvalum I™* - contains zinc and mercury for use in seawater

Galvalum II™* - contains zinc and mercury for use in saline mud

Galvalum III™ - contains zinc and indium for use in seawater, brackish water, and saline mud

** Seldom used due to mercury content.*

Galvanic anodes are available in a wide range of shapes and sizes for specific applications. Custom shapes and sizes can be made.

For marine environments (platforms), dual galvanic anodes can be made with a highly active anode metal casing (e.g., magnesium) on a less active anode core (e.g., zinc). These are used to provide a high initial current density to achieve initial cathodic protection polarization on offshore structures. Once the protection potential is achieved, the less active anode can maintain an adequate cathodic protection polarization.

Galvanic Anode Efficiency

The efficiency of a galvanic anode depends on the alloy of the anode and the environment in which it is installed. The consumption of any metal is directly proportional to the amount of current discharged from its surface. For galvanic anodes, part of this current discharge is due to the cathodic protection current provided to the structure and part is caused by local corrosion cells on its surface. Anode efficiency is the ratio of metal consumed producing useful cathodic protection current to the total metal consumed. For magnesium, the anode efficiency is generally less than 50%, while zinc has an efficiency of 90%.

Applications of Galvanic Anode Systems

The following are among the conditions where galvanic anodes are used:

- When a relatively small amount of current is required.
- Usually lower resistivity electrolytes.
- For local cathodic protection to provide current to a specific area on a structure. Some pipeline operators install galvanic anodes at each location where a leak is repaired rather than installing a complete cathodic

protection system. Such practices may be encountered on bare metal or very poorly coated systems where complete cathodic protection may not be feasible because of cost.

- When additional current is needed at problem areas. Some structures with overall impressed current cathodic protection systems may have isolated points where additional current in relatively small amounts is needed. These requirements can be met with galvanic anodes.
- Poorly coated buried valves
- Interiors of water storage tanks
- Shorted casings that cannot be cleared (to improve potentials in the surrounding area)
- Underground storage tanks
- Isolated sections where the coating has been badly damaged
- Areas where electrical shielding impairs effective current distribution from remotely located impressed current systems
- In cases of cathodic interference, if the conditions are suitable, galvanic anodes can be used at the discharge point to return interfering current.
- To provide protection to structures located near many other underground metallic structures where conditions make it difficult to install impressed current systems without creating stray current interference problems. Galvanic anodes can be an economical choice for a cathodic protection current source under such conditions.
- Galvanic anodes find extensive use in protecting the interior surface of heat exchanger water boxes and other vessels. They are also used within oil heater-treater vessels, depending on the quality of the interior lining and the fluid chemistry and temperature.
- On offshore structures, large galvanic anodes may be used to protect the underwater components.

Anode Backfill

Zinc and magnesium anodes used in cathodic protection applications in soil are sometimes supplied prepackaged with a prepared backfill material in a cloth or cardboard container. The special backfill prevents direct soil contact to reduce localized corrosion of the anode, prevents passivation of the anode caused by reactions with soil salts, provides a low-resistivity environment around the anode, and expands when wet to fill the hole and eliminate air voids. The most common backfill material contains 75% hydrated gypsum, 20% bentonite clay, and 5% sodium sulfate. Zinc anodes can also be packaged in a backfill consisting of 50% hydrated gypsum and 50% bentonite clay. Since zinc anodes are normally installed in low-resistivity soil, it is not necessary to add sodium sulfate to lower resistivity.

Wiring and Connections

Galvanic anodes can be attached to the structure either directly by welding or bolting integral straps to the structure, e.g., hull mounted anodes and bracelet anodes, or by connecting a wire between the anode and structure.

If a wire is used, the manufacturer attaches it to the anode. The wire is attached to the structure using a mechanical connection, thermite weld, or other suitable method. The thermite weld is the preferred method since it provides the most reliable connection. The wire should be coated with a dielectric insulation and the connections should be coated.

Components of Impressed Current Cathodic Protection

The components of an impressed current cathodic protection system are anodes, anode backfill, a power supply (rectifier), structure, wiring, and connections. The anodes used in impressed current CP systems are different from those used in galvanic systems. Impressed current anodes are manufactured from materials that are consumed at low rates. Impressed current CP systems generally operate at higher current and driving voltage levels than galvanic anode CP systems.

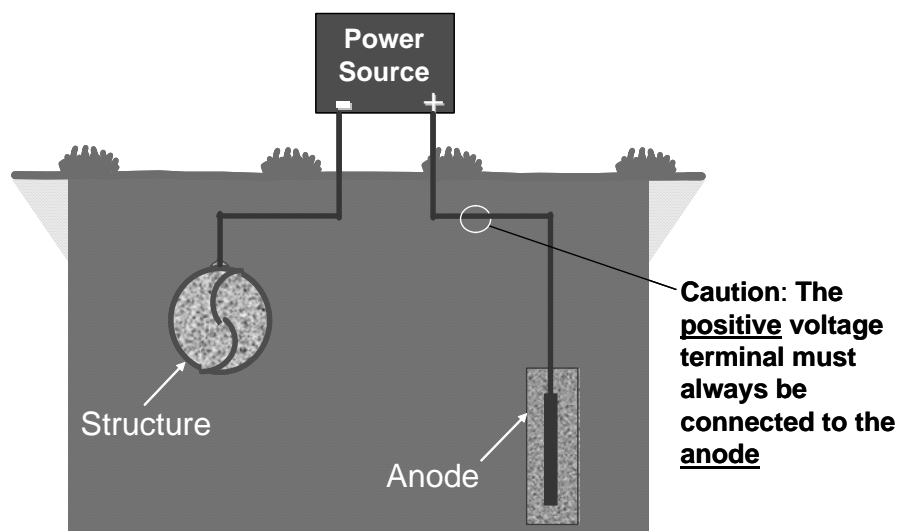


Figure 3.3 Typical Impressed Current Cathodic Protection

Applications of Impressed Current Cathodic Protection

Typical uses of impressed current are:

- for large current requirements, particularly for bare or poorly coated structures
- in all electrolyte resistivities
- as an economical way of protecting structures having dissipated galvanic anodes
- to overcome stray current or cathodic interference problems
- for protection of large heat exchanger water boxes, oil heater-treaters, and other vessels
- for interiors of water storage tanks
- for exterior bottoms (both primary and secondary) of aboveground storage tanks
- for underground storage tanks
- for underwater components of offshore structures
- for foundation piles and sheet piling, both underground and in the water.

Anodes

- Graphite

Graphite anodes are used in soils, flowing seawater, and mud. They are practically immune to chlorine attack. Graphite anodes are usually impregnated with a sealer to prevent mechanical failure from gas evolution in pores. Graphite is also brittle. Consumption rates are 0.45 kg/A-y (1 lb/A-y) in seawater, 0.9 kg/A-y (2 lb/A-y) in carbon backfill, and 1.36 kg/A-y (3 lb/A-y) in mud. Graphite anodes are usually available as cylindrical anodes.

- Conductive Polymer

Carbon is used as filler in polymer materials having a copper core for use as an impressed current anode. This type of anode looks like an insulated wire but the covering is conductive. (Note: this type of anode wire must not be used where dielectrically insulated wire is needed.) This material has a maximum rating of 51 mA/m (16 mA/ft) of material.

Carbon has also been used as conductive filler in water- or solvent- based coatings for application as an anode to protect reinforced concrete structures.

- High-Silicon Chromium-Bearing Cast Iron

High-silicon cast iron (HSCI) is a chemically resistant alloy containing silicon, chromium, and iron. HSCI anodes are commonly used in fresh water, seawater, or underground applications. HSCI is very brittle and forms a SiO_2 film on the surface in underground applications that can increase the resistance of the anode in dry environments. The consumption rate of HSCI ranges from 0.25 to 1 kg/A-y (0.55 to 2.20 lb/A-y).

- Lead

Lead-silver alloys have been used in seawater applications. The lead under anodic current develops a PbO_2 film that is conductive and prevents deterioration of the lead. The consumption rate of lead-silver alloys is on the order of 0.09 kg/A-y (0.2 lb/A-y).

Extruded lead with platinum pins has also been used in seawater applications. The purpose of the platinum pins is to promote the formation of the PbO_2 film.

- Mixed-Metal Oxide

Mixed-metal oxide (MMO) anodes, also called dimensionally stable anodes, consist of rare earth oxides baked onto a titanium substrate. These anodes were developed for the electrolytic production of chlorine and hypochlorites, but are now used for cathodic protection applications. The consumption rate is on the order of 1 mg/A-y. This anode material is typically available in rod, wire, tubular, or mesh form.

- Platinum

Platinum is used as an anode material when either metallurgically clad or plated onto either a titanium or niobium substrate. Titanium and niobium form stable oxide layers when made anodic. These layers are stable up to 12 V in the case of titanium and 90 V in the case of niobium. The consumption rate of platinized anodes is on the order of 6 to 10 mg/A-y. Platinized anodes are available in wire or mesh form. Platinized anodes are subject to rapid deterioration if the breakdown voltage is exceeded or if the environmental conditions surrounding the anode become acidic. Other deleterious factors include the presence of low-frequency AC ripple, current reversal, biofouling, scales, and the presence of certain organic materials.

Platinized anodes are most suitable in fresh-or salt-water applications rather than in underground applications.

- Scrap Metal

Scrap iron or steel can be used as an anode material. In situations where the current requirements are low, scrap iron is readily available, and the anode can be readily replaced, scrap iron might be an economical choice. The consumption rate of iron is 6.8 to 9.1 kg/A-y (15 to 20 lb/A-y). The relatively rapid dissolution rate and difficulty in maintaining the integrity of the connection between the power supply and anode are disadvantages of this material.

- Metallized Titanium

Metallized titanium is being tested for use on reinforced concrete structures. The titanium is first sprayed to the concrete surface using an arc spray technique and then a liquid catalyst is applied to activate the anode.

- Thermal Sprayed Zinc and Aluminum Alloys

Thermal sprayed zinc and aluminum alloys have been used as impressed current anodes on reinforced concrete structures. The relatively low current requirement for this type of structure has made the use of zinc and aluminum alloys practical in these applications.

- Magnetite

Magnetite is a sintered material made up of Fe_3O_4 . It is used in seawater, brackish water, fresh water, and high-resistivity soil. The consumption rate of magnetite is 0.005 to 0.08 kg/A-yr. Magnetite is available in cylindrical form.

- Aluminum

Aluminum has also been used as an impressed current anode, primarily in fresh water applications such as water storage tanks. The dissolution rate of aluminum as an impressed current anode is about 4.5 kg/A-y (10 lb/A-y).

Anode Backfill

Carbon is used as a backfill material around impressed current anodes for underground CP applications. The purpose of the backfill material is to:

- reduce the resistivity of the environment surrounding the anode to increase the amount of current the anode can discharge
- extend the anode surface area, thus increasing the amount of current the anode can discharge; and
- reduce consumption of the anode since the carbon becomes the part of the anode consumed before the anode itself.

Carbon backfill for cathodic protection purposes is available as calcined petroleum or metallurgical coke, each being the product of its respective industry. Non-calcined carbon is also available, but is not suitable for CP use since it can have too high an electrical resistance.

The typical composition of carbon backfill is:

	Metallurgical	Calcined
Carbon	85%	99%
Ash	8 to 10%	0.1%
Moisture	6 to 9	0%
Sulfur	1%	
Volatile matter	3%	<0.5%
Density kg/m ³ (lb/ft ³)	730 (45)	875 to 1,200 (54 to 74)

The resistance of carbon backfill is dependent on how well it is compacted. The higher the degree of compaction, the lower the resistance. The size of the carbon particles is important in compaction. A mixture of large and small sizes is advisable to attain good density and low resistance. The size range may be on the order of 0.5 to 12.7 mm (0.02 to 0.5 in.). Finer grade coke is often used for deep anode systems and the particles may range from 0.10 to 1 mm (0.004 to 0.04 in.) in size.

Impressed current anodes for underground applications can be supplied prepackaged in carbon backfill. The carbon backfill and anode are packaged in an individual galvanized steel canister. Carbon backfill for deep anode systems is added during installation of the anode bed by pumping a fluidized mixture of

water and carbon backfill to the bottom of the hole and allowing the carbon particles to settle out.

Power Supply

Unlike galvanic anode systems where the natural potential difference between the anode and cathode provides the driving force for current, an impressed current CP system must be supplied with power from an external source. Cathodic protection power supplies are covered in Chapter 4.

Wiring and Connections

In impressed current CP systems, all wiring and connections must be made to totally isolate the metal from the electrolyte. Unlike a galvanic anode system where exposed wire and connections are protected by the anode, any exposed metal in an impressed current CP system is part of the **anode**. Thus, exposed metal will corrode rapidly. Only cable having approved cathodic protection dielectric insulation can be used. Types of insulation found on CP cables include:

- High-Molecular-Weight Polyethylene (HMWPE)

This insulation is commonly used for direct burial cathodic protection installations for both anode and structure wiring. The insulation for cathodic protection cable (type CP) is thicker than standard polyethylene insulation (e.g., THW). HMWPE insulation is not recommended for use in environments containing chlorine, hydrochloric acid, or petroleum hydrocarbons.

- Halar/Polyethylene Layered Insulation

Halar/polyethylene is a dual jacketed insulation. The outer jacket (HMWPE) provides mechanical protection to the wire as well as chemical resistance and dielectric insulation. The inner jacket is Halar, which is a thermoplastic fluoro-copolymer which is resistant to chemicals, including chlorine, hydrochloric acid, sulfuric acid, petroleum hydrocarbons, alkalis, and strong oxidizing acids. The temperature range of this insulation is -62°C (-80°F) to 121°C (250°F).

- Kynar/Modified Polyolefin

Kynar (polyvinylidene fluoride)/modified polyolefin is a dual jacketed insulation similar to Halar/polyethylene. The outer jacket (HMWPE) provides mechanical protection to the wire as well as chemical resistance

and dielectric insulation. It is resistant to chlorine, hydrochloric acid, sulfates, hydrogen sulfides, alkalis, other acids, petroleum-based chemicals, and chlorine gas.

- **EPR/CSPE Layered Insulation**

EPR/CSPE is also a dual jacketed insulation. The outer insulation is a chlorosulfonated polyethylene (CSPE) and is ductile and notch resistant. This insulation is resistant to acids and petroleum hydrocarbons. The inner insulation is ethylene propylene (EPR), which is resilient and resistant to most organic and inorganic substances.

Total encapsulation of splices and connections is required to prevent water from getting into the splice, which will eventually destroy the connection. Encapsulation is achieved using an epoxy resin cast into a mold around the splice, heat-shrink sleeves containing adhesive mastic manufactured for CP purposes, or multi-component wrapped connections. Prior to applying the splicing material, the wire should be thoroughly cleaned to remove greases, oil, and dirt. The wire insulation should be lightly abraded prior to applying the splice. This is one area where a little care will prevent lots of problems later on.

Splices should be avoided if possible, especially in the anode circuit.

Environmental Issues

Deep anode CP systems present environmental concerns as the borehole can penetrate different geological layers and water aquifers. The layers must be sealed to prevent the transfer of undesirable components, such as pollution, between layers. This can be done through the use of clay sealing materials or specialized conductive cementitious backfills.

The primary reactions at the anode surface are:

- metal oxidation
- oxygen and chlorine evolution, and
- chlorine generation.

Galvanic anodes and impressed current anodes release small quantities of corrosion products as they deteriorate. The corrosion products of carbon anodes and carbonaceous backfill are gases – carbon monoxide and carbon

dioxide. The corrosion products of high-silicon cast iron anodes are the same as those produced from iron-based alloys. These tend to stay in close proximity to the anode in soil. Dimensionally stable anodes produce few if any of these products. Gases, including chlorine, oxygen, carbon dioxide, and carbon monoxide (depending on the anode and the environment) are produced by anodes. These gases can be flammable, poisonous, or corrosive and can block the groundbed reducing anode performance. The gases need to be vented, particularly in deep anode systems.

Reactions at the anode produce an excess of hydrogen ions.



These will acidify the environment immediately adjacent to the anode, but this is usually not significant since the environment away from the anode neutralizes the acid.

Sacrificial anodes installed on ship hulls or in applications where they are immersed in a natural water environment (e.g., pond, bay, river, and ocean) will corrode releasing corrosion products into the water. Whether or not this is an environmental concern depends on the relative water volume compared to the volume and nature of the corrosion products released. Aluminum anodes containing mercury can be used in open seawater and saline mud, but not in fresh water (aluminum containing indium is used in these applications).

Anodes and other cathodic protection materials to be installed into potable water tanks or other potable water systems must have approval of NSF International. ANSI/NSF 60, “Drinking Water Treatment Chemicals,” and ANSI/NSF 61, “Drinking Water System Components – Health Effects,” list materials approved for use in contact with potable water.

Anode Configurations

The objective of cathodic protection is to supply the structure being protected with adequate current for cathodic polarization to occur. This means that anodes must be located to distribute current as evenly as possible to the structure. Previous discussion introduced the various types of anodes used – galvanic and impressed current. Anode configurations can be described as *distributed* or *remote*.

Current from the anode through the electrolyte produces voltage drops from point to point in the electrolyte (gradients). The magnitude of the gradient is dependent on the amount of current, the electrolyte resistivity, and the distance between points. The anode gradients are largest within a few feet of the anode. The term *remote earth* refers to the point where further distance from the anode produces no further change in voltage gradient.

A *distributed* configuration uses anodes located at relatively close intervals along the structure. The anodes are spaced close together and close to the structure so as to distribute the current evenly over the surface of the structure and to raise the potential of the earth adjacent to the structure (Figure 3.4). “Close” means that the structure being protected will fall within the anode voltage gradient. This means that the anodes will cause the electrolyte around the structure to become positive with respect to remote earth (Figure 3.5). The definition of “close” is not firm, but is usually within ten to fifteen feet of the structure. Situations where distributed anode systems are used include uncoated structures, structures that are not electrically isolated from other structures, and in congested areas, where shielding or interference is possible.

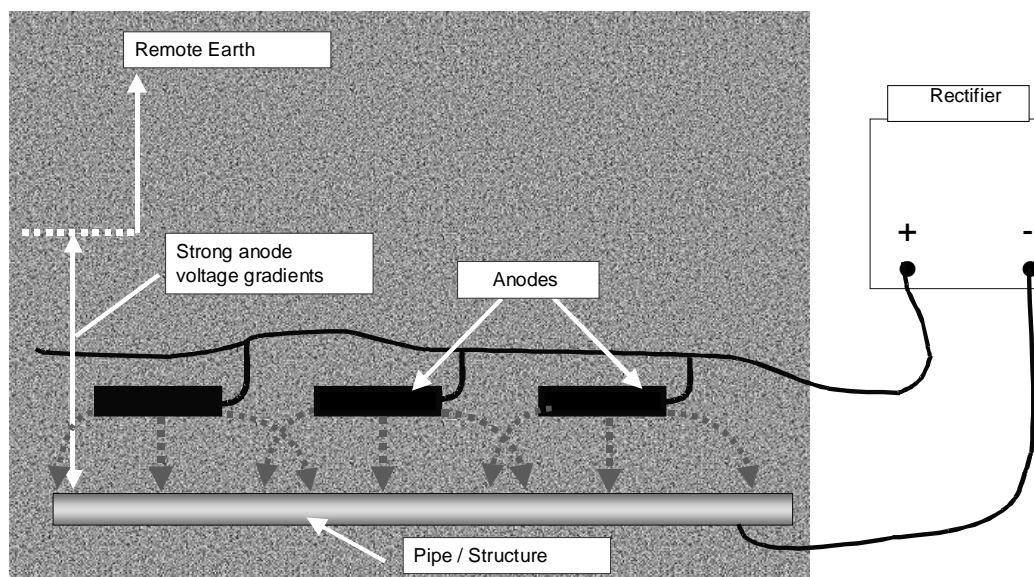


Figure 3.4 *Illustration of a Distributed Anode System (the anodes are placed so that the structure is within the anode voltage gradient)*

Cathodic protection systems for reinforced concrete use a distributed anode configuration consisting of a continuous anode on the concrete surface or closely spaced strips embedded in the concrete surface.

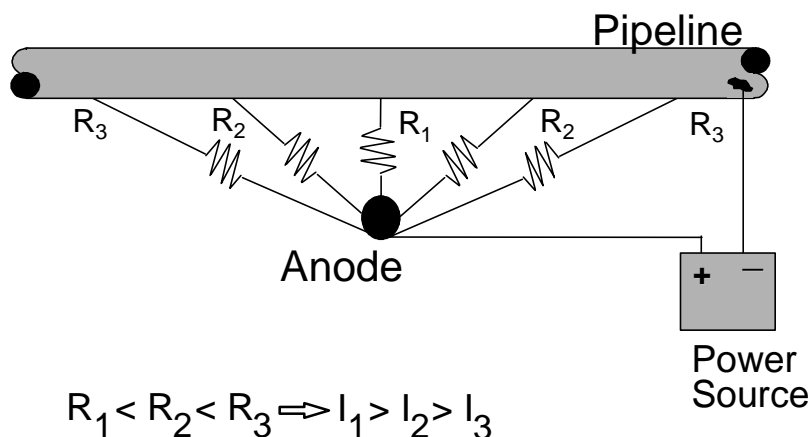


Figure 3.5 *Current Distribution from a Close Anode*

A *remote* configuration (Figure 3.6) uses anodes placed at a location considered electrically remote from the structure. The term *electrically remote* is not necessarily the same as *geometrically remote* (Figure 3.7). Remote anodes are used for coated structures where only holidays in the coating are protected by the CP system and for structures that are electrically isolated from other structures. In these cases, the only metal requiring cathodic protection is at holidays in the coating. These holidays can be defined as electrically remote from the anode.

All anodes can be installed either horizontally or vertically. The choice of whether to use a horizontal or vertical groundbed depends on the conditions present at the groundbed location.

- Vertical groundbeds may be easier to install, requiring augering a hole rather than digging a ditch.
- Vertical groundbeds, in general, require less room and less excavation.
- Vertical anodes might have a lower resistance than horizontal anodes installed under the same conditions.
- Soil conditions, i.e., resistivity layering or rock formations, might prevent the use of vertical anodes.
- Site geometry might require one or the other type of groundbed.

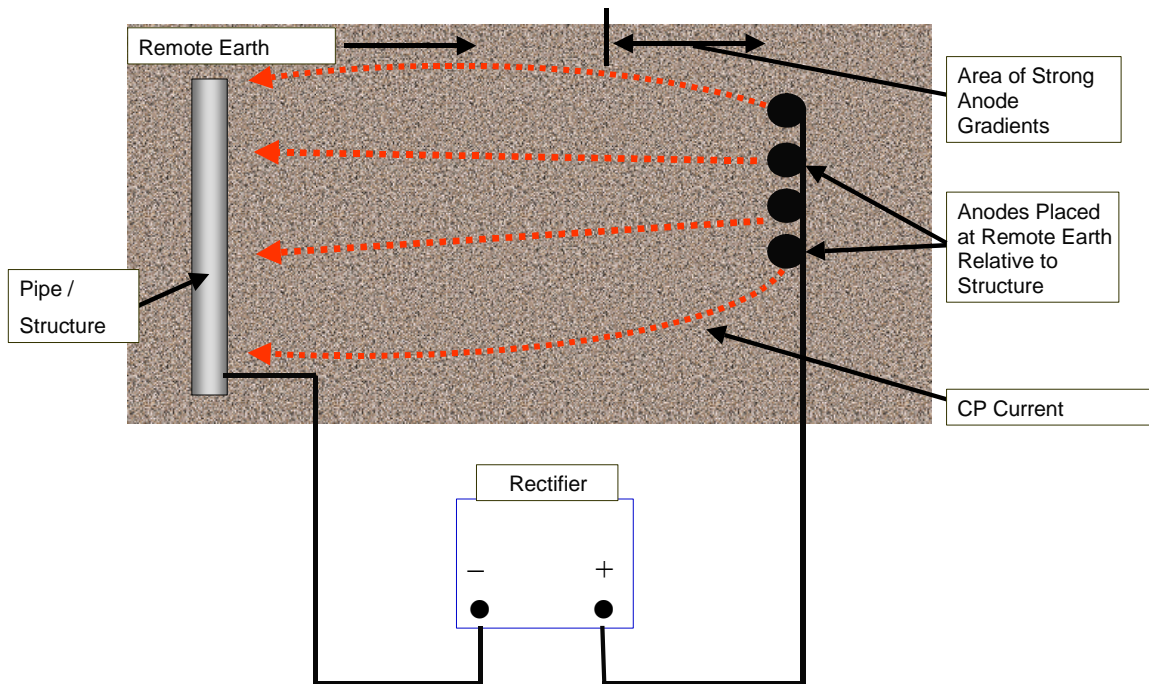


Figure 3.6 Illustration of a Remote Anode

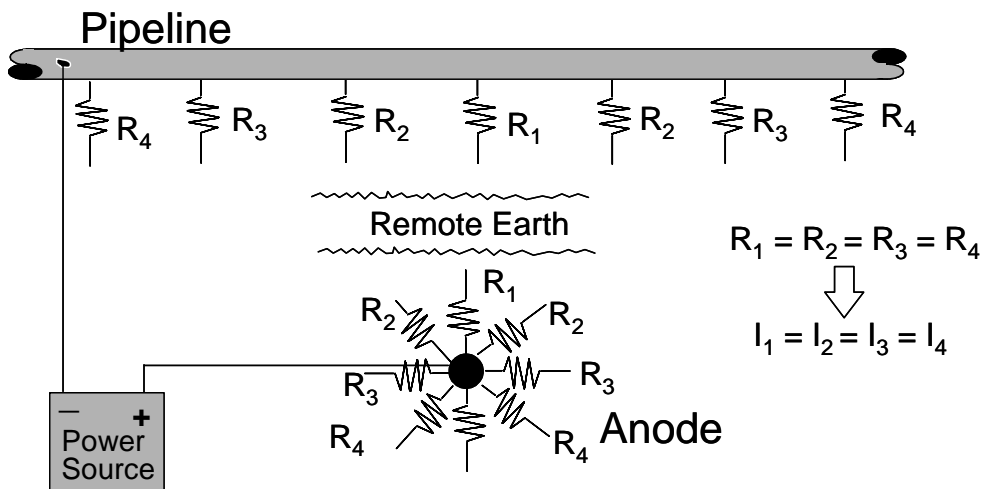


Figure 3.7 Current Distribution for a Remote System

Galvanic Anodes

Galvanic anodes can be placed in either a distributed or remote fashion. Galvanic anodes are usually buried at relatively shallow depths at or below the ground water level, e.g., at or below pipe depth. Magnesium and zinc are available as continuous ribbon to allow use as one continuous distributed anode.

Galvanic anodes for atmospherically exposed reinforced concrete structures are placed over the entire surface to distribute the current evenly.

Galvanic anodes are usually installed in a distributed manner on offshore platforms. The anodes are directly connected to the platform.

Impressed Current Anodes

Impressed current anodes are installed either as distributed or remote anodes. Anodes can be installed in surface groundbeds (up to 7.62 m [25 ft] deep). In addition, impressed current anodes are used in the remote configuration by installing them in a deep hole drilled from the surface. These are called *deep anodes*. Deep anodes are at least 15.24 m (50 ft) deep. Semi-deep anodes are 7.62 to 15.24 m (25 to 50 ft) in depth. Deep anodes can be several hundred feet deep to achieve the remote anode configuration. Figure 3.8 illustrates a deep anode configuration.

In the case of a buried pipeline or elongated structure (e.g., sheet pile wall), anodes can be placed parallel to a structure or perpendicular to the structure. Parallel or distributed placement of the anodes results in the current being evenly distributed along the length of the structure. This configuration “closely couples” the anode to the structure and is useful in situations where the structure is not well coated or where other nearby structures might be subjected to interference. A parallel or distributed configuration might be needed if there is insufficient right-of-way for a remote anode bed. Perpendicular anode placement can be used where the structure is well coated, where current requirements are relatively low, and where property access permits.

Anode placement on atmospherically exposed reinforced concrete structures (e.g., bridges and buildings) requires that a distributed anode be used. Normally this means placing the anode over the entire surface of the concrete (e.g., metallized coating, anode mesh, or conductive paint) or using closely spaced anode strips (e.g., ribbon).

Impressed current anodes used in condenser water boxes are distributed to provide uniform current and are also placed to achieve current to hard-to-reach areas such as corners.

Impressed current anodes are installed in a distributed manner on offshore structures to evenly distribute current to the structure.

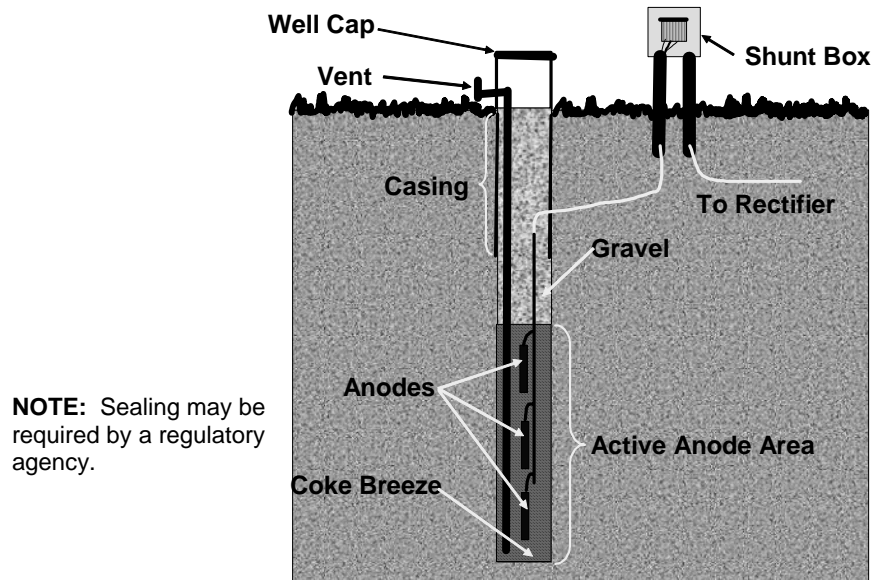
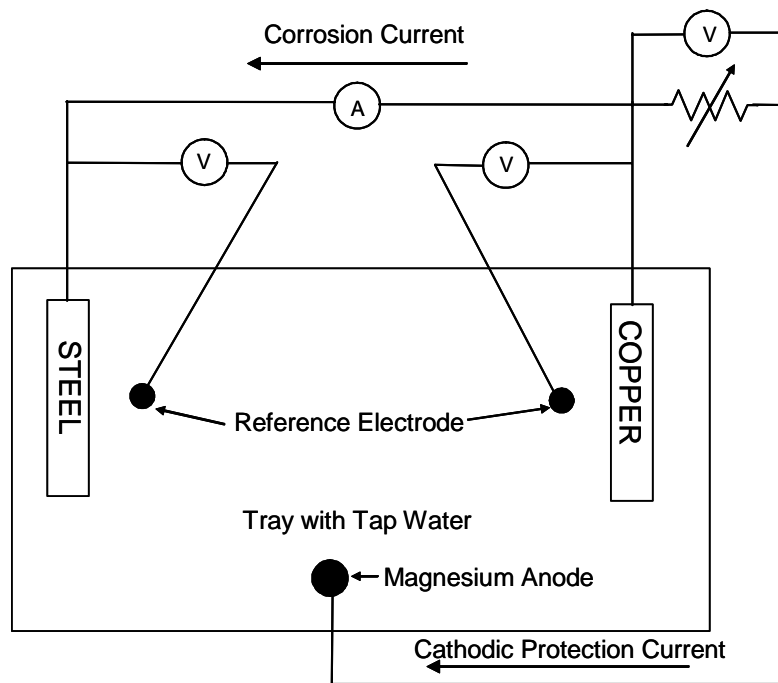


Figure 3.8 Deep Anode Remote System

Experiment 3.1 Demonstrate the Use of a Sacrificial Anode to Mitigate Corrosion in a Local Action Cell

The operation of a sacrificial anode cathodic protection system can be demonstrated as illustrated below. In this experiment the steel and copper represent a local action corrosion cell. Corrosion in this cell is mitigated by cathodic protection.

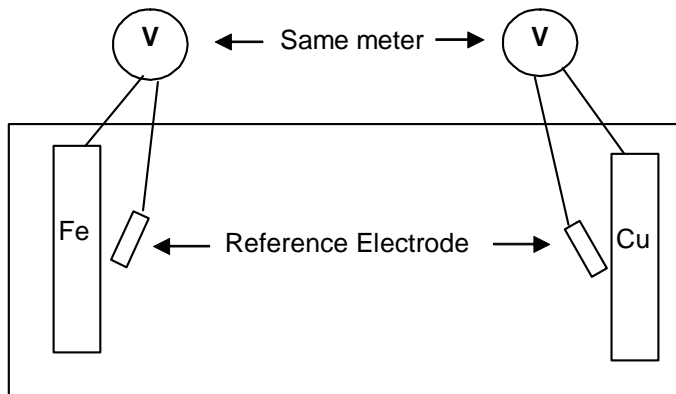


Experiment to Demonstrate Corrosion Mitigation of Local Action Cells by Sacrificial Anode Cathodic Protection

PROCEDURE

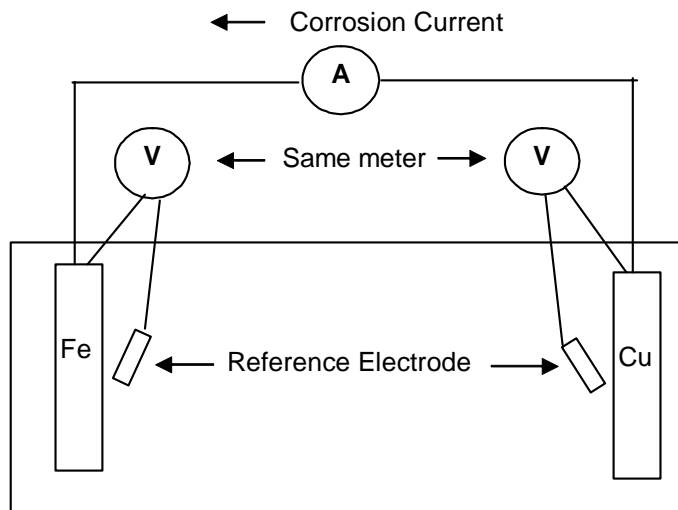
Part A

1. Insert steel and copper sheet in side of tray and add water.
2. Measure static potential of steel and copper.



3. Connect ammeter between copper and steel sheet and measure corrosion current (I_{corr}).

Leave ammeter in place once installed

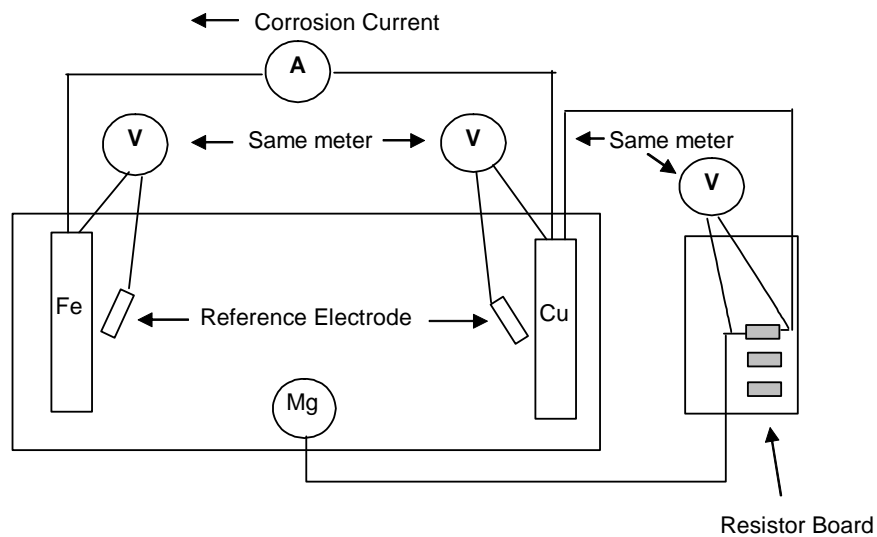


4. Measure polarized potentials of steel and copper.

Part B

1. Place magnesium anode in tray and connect to the copper sheet through a 10,000- Ω resistor.
2. Measure corrosion current (I_{corr}).
3. Determine the cathodic protection current ($I_{\text{c,p}}$) by calculating it from the voltage drop across the resistor.
4. Measure polarized potentials of steel and copper.

Leave ammeter in place once installed

**Part C**

1. Repeat Part B using 1,000- Ω , 100- Ω , and 10- Ω resistors.

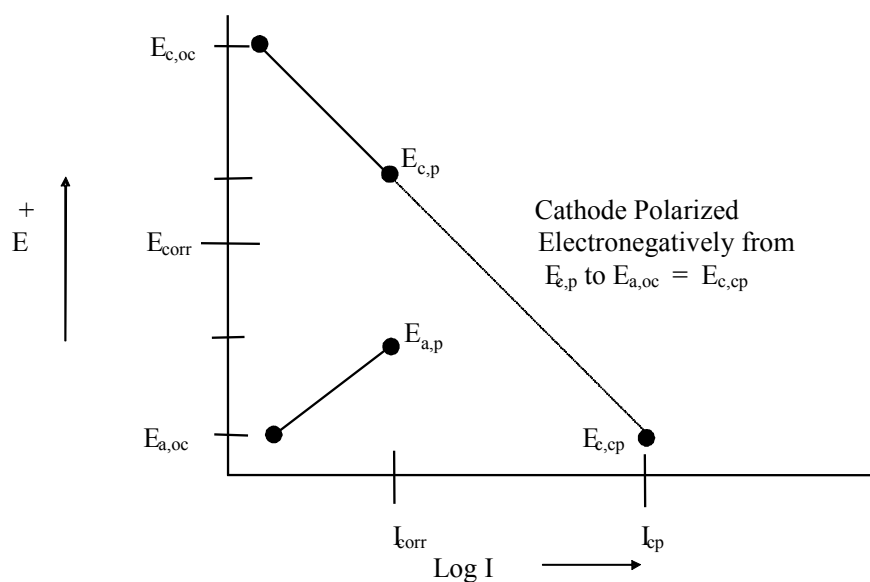
Part D

1. Construct polarization diagram.
(See example next page)

RESULTS

Circuit Conditions	E_{steel} (mV _{CSE})	E_{copper} (mV _{CSE})	Corrosion Current I_{corr} (mA)	CP Voltage Drop (V_r) Across Resistor (mV)	Calculate CP Current $I_{\text{c,p}}$ (mA)
Static (OC)	$E_{a, oc}$ _____	$E_{c, oc}$ _____			
Polarized	$E_{a, p}$ _____	$E_{c, p}$ _____			
10,000 Ω	_____	$E_{c, cp}$ _____	_____	_____	_____
1,000 Ω	_____	_____	_____	_____	_____
100 Ω	_____	_____	_____	_____	_____
10 Ω	_____	_____	_____	_____	_____

Polarization Diagram Example



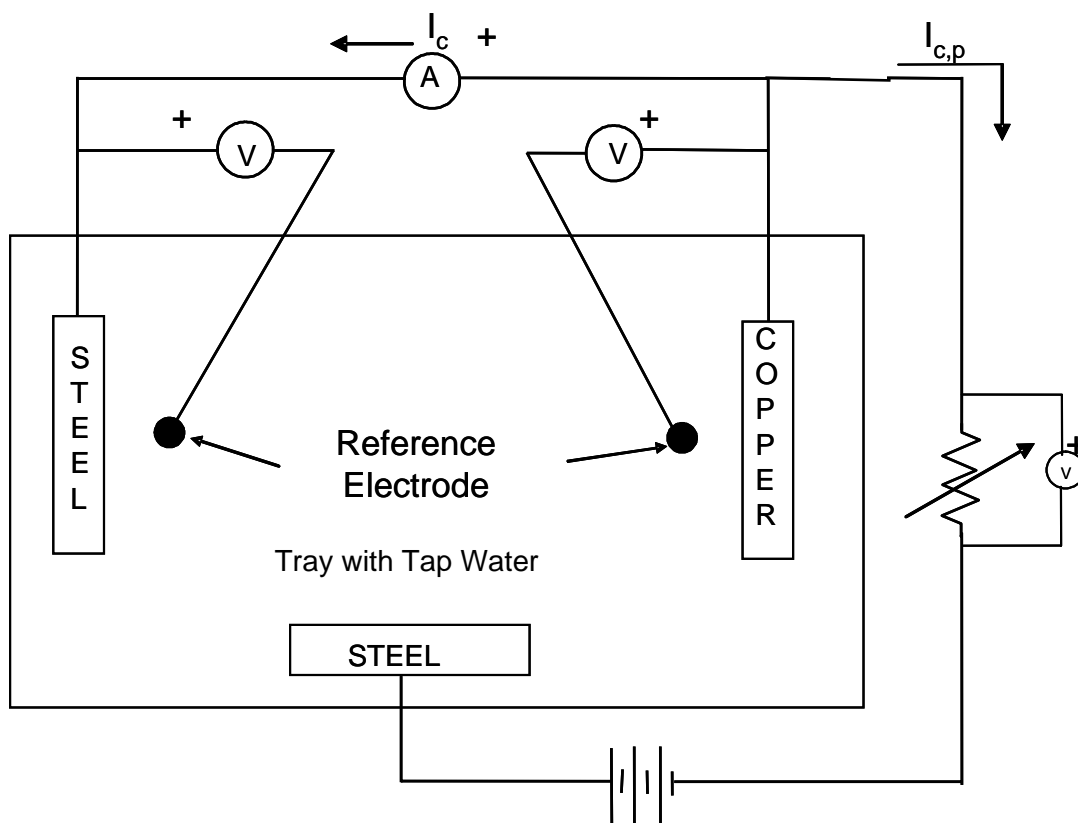
CONCLUSIONS

Corrosion current decreases as cathodic protection current increases.

Corrosion current decreases as polarized potential of cathode is made more electronegative.

(Option To Experiment 3.1)**Experiment 3.2 Demonstrate the Use of an Impressed Current System to Mitigate Local Action Cell Corrosion**

The operation of an impressed current cathodic protection system can be demonstrated as illustrated in the figure below.



Experiment to Demonstrate Corrosion Mitigation of Local Action Cells by Impressed Current Cathodic Protection

PROCEDURE

Part A

1. Insert steel and copper sheet in side of tray and add water.
2. Measure open circuit static potential of steel and copper.
3. Connect ammeter between copper and steel sheet and measure the corrosion current.
4. Measure the polarized potential of steel and copper.

Part B

1. Place second steel sheet (anode) in opposite side of tray and connect to the positive side of the battery (power source) via a 10,000- Ω resistor. Connect the negative side of the battery to the copper sheet.
2. Measure the corrosion current (I_{corr}).
3. Determine the cathodic protection current ($I_{\text{c,p}}$) by measuring the voltage drop across the resistor and calculating the current using Ohm's Law.
4. Measure the polarized potentials of steel and copper.

Part C

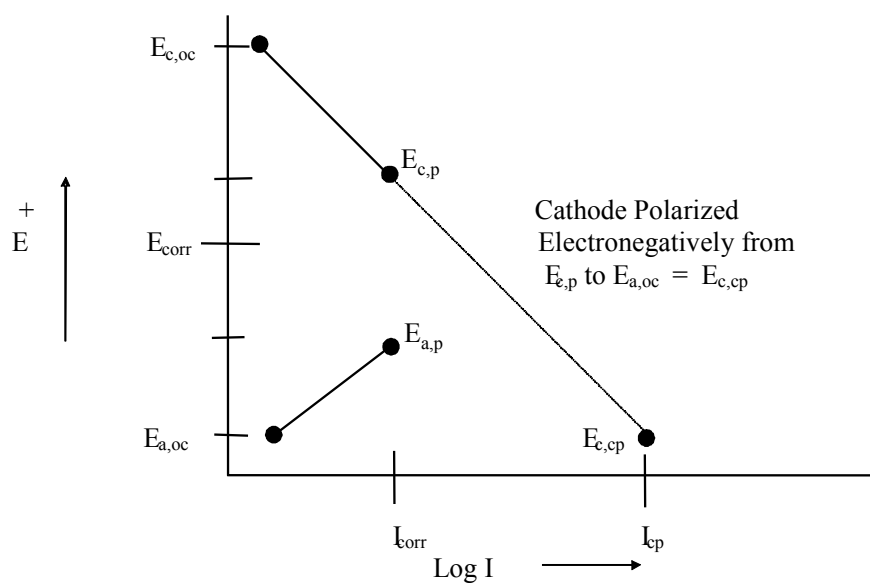
1. Repeat Part B using 1,000- Ω , 100- Ω , and 10- Ω resistors.

Part D

1. Construct a polarization diagram (see example on next page).

RESULTS

Circuit Conditions	E_{steel} (mV _{CSE})	E_{copper} (mV _{CSE})	Corrosion Current I_{corr} (mA)	CP Voltage Drop (V_r) Across Resistor (mV)	Calculate CP Current $I_{\text{c,p}}$ (mA)
Static (OC)	$E_{a,oc}$ _____	$E_{c,oc}$ _____			
Polarized	$E_{a,p}$ _____	$E_{c,p}$ _____			
10,000 Ω	_____	$E_{c,cp}$ _____	_____	_____	_____
1,000 Ω	_____	_____	_____	_____	_____
100 Ω	_____	_____	_____	_____	_____
10 Ω	_____	_____	_____	_____	_____



Example of Polarization

CONCLUSIONS

1. Corrosion current decreases as cathodic protection current increases.
2. Corrosion current decreases as the polarized potential of the cathode becomes more electronegative.
3. More cathodic protection current and, therefore, more polarization can be achieved with impressed currents than with a sacrificial system.

CHAPTER 4

DC Power Sources for Cathodic Protection

Depending on economics any source of DC power can serve as an impressed current power source and may consist of:

- Transformer-rectifier (rectifier)
- Thermoelectric Generators (TEG)
- Solar Power
- Wind-Driven Generators
- Engine Driven Generators
- Batteries
- Fuel Cells

Transformer-Rectifier

The most common type of power supply used for impressed current cathodic protection is a transformer/rectifier, commonly referred to simply as a *rectifier*. A rectifier converts the AC power supply voltage to the required output voltage and then converts it to DC.

Rectifiers are either supplied in ventilated cases to allow convective air cooling or are immersed in transformer oil. Rectifiers are normally powered by an AC power system.

The rectifier input is an AC voltage from the commercial electrical power grid or an engine-generator. A transformer with tap adjustments in the secondary side provides a method to reduce and adjust the output voltage level and to isolate the DC circuit from the input power system. A rectifying circuit next converts the adjusted AC voltage to produce a DC voltage output.

The basic units of a rectifier consist of:

- AC Supply
- Circuit breaker
- Transformer
- Rectifying elements
- Meters
- DC Output Terminals
- Fuses*
- Surge protection*

* *depending on unit*

Circuit Breakers

The primary function of a circuit breaker is to provide protection to the rectifier components from current surges or overload. A secondary function is to act as an AC disconnect when working on the face of the panel.

CAUTION: Circuit breaker contacts can “weld” together and not open when the lever is in the tripped position. Confirm that power is off by measurement before proceeding.

Circuit breakers are normally installed in the AC supply with the trip lever exposed on the rectifier panel. In a 115 V_{AC} supply a single rectifier in the “hot” line is installed but with 230 V_{AC} or higher, a dual breaker with linked trip levers are used with a breaker in each line. Three phase units will have a breaker in each of the three lines with linked trip levers.

There are three types of circuit breakers which are described below.

Thermal Breakers

These breakers have a bimetallic element that carries current. An excessive amount of current will heat the element causing the two metals to expand but at different expansion rates since they are selected for their different temperature coefficients (Figure 4.1). The element is then pulled to one side thus breaking the connection. The element must cool before it can be reset.

The thermal breaker is dependent on the ambient temperature allowing more current in a cold environment or less current in a hot environment to pass before opening.

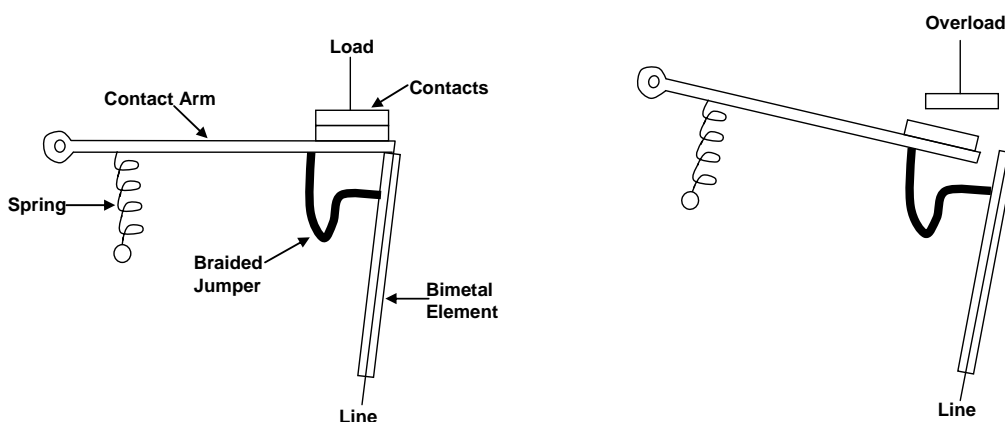


Figure 4.1 Thermal Breaker Mechanisms

Magnetic Breaker

The magnetic breaker consists of an iron core surrounded by a coil of wire acting as an electromagnet. When the current increases beyond the rating the magnetic field created will cause the core to pull a trip lever towards it thus causing an open circuit (Figure 4.2). Under high current surges the breaker will trip immediately and is considered the most suitable for CP rectifiers.

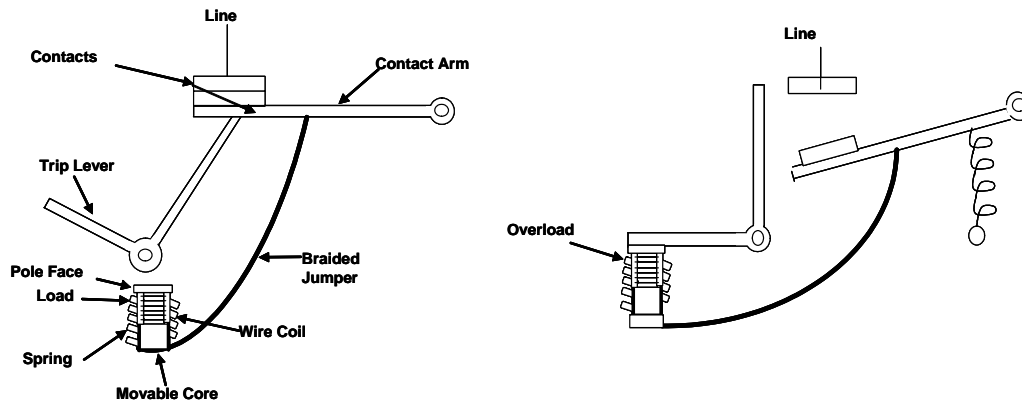


Figure 4.2 Magnetic Breaker Mechanisms

Thermal Magnetic Breakers

The thermal-magnetic breaker is similar to a thermal breaker except that it has a magnetic plate attached to the element to increase the speed in tripping the circuit (Figure 4.3). A large surge of current creates a magnetic field around the plate that in turn is attracted to another plate thus tripping the circuit before the element itself reacts due to overheating.

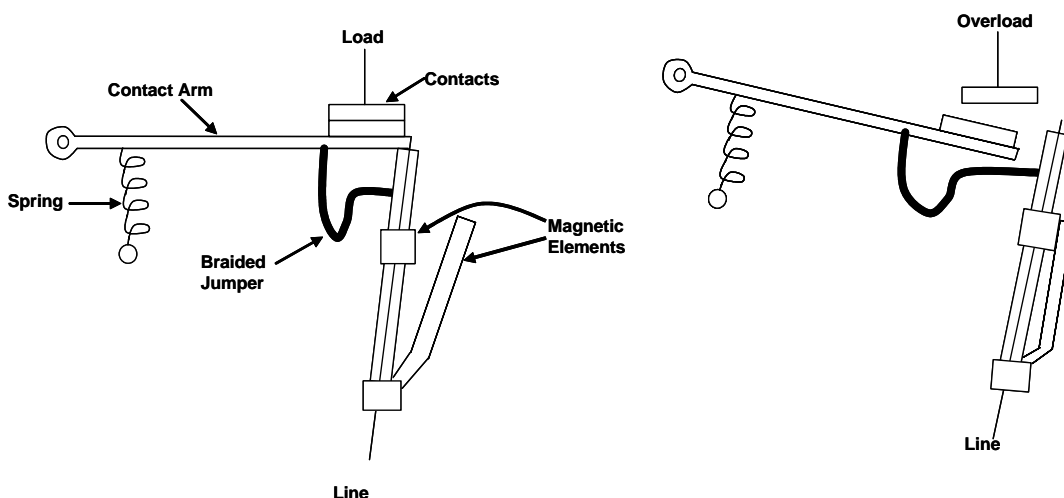


Figure 4.3 Thermal Magnetic Mechanisms

Although faster than the thermal breaker it has a slower reaction time to the magnetic breaker and can be used where an interrupter continues to trip the breaker.

Transformer

The purpose of a transformer is to either “step up” or “step down” an AC supply voltage. It could also be used as an isolation transformer at the same voltage. Depending on the design of the transformer it can provide an adjustable range of secondary AC voltages.

The transformer consists of an iron core with two sets of wires coiled around it. One coil, the primary windings, is connected to the primary AC voltage supply and the alternating magnetic field induces an AC voltage in the second coil or the secondary windings through this magnetic couple (Figure 4.4).

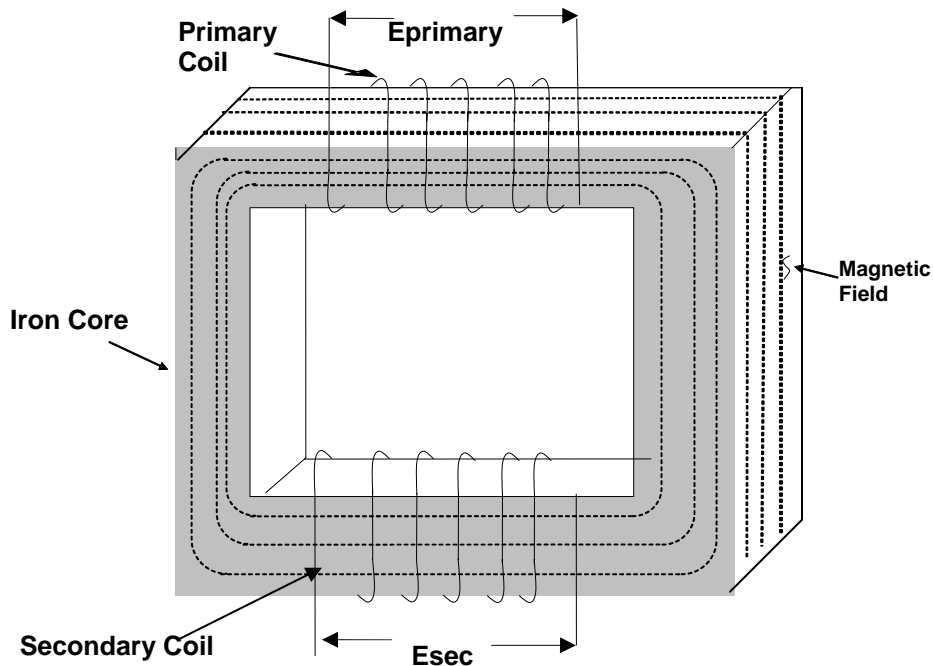


Figure 4.4 Transformer Schematic

The ratio of the primary AC voltage to the induced secondary AC voltage is in proportion to the windings in each coil (Equation 4.1).

$$\frac{E_{\text{primary}}}{E_{\text{secondary}}} = \frac{\text{Primary Turns}}{\text{Secondary Turns}} \quad \text{Eq. 4-1}$$

Example:

If a transformer has no losses, what is the secondary voltage of a transformer being supplied with 115 V_{AC} that has 400 turns on the primary and 100 turns on the secondary windings?

Rearranging equation 4-1:

$$E_{\text{secondary}} = \frac{E_{\text{primary}} \times \text{Secondary Turns}}{\text{Primary Turns}}$$

$$E_{\text{secondary}} = 115 \text{ V}_{\text{AC}} \times 100 / 400 = 28.75 \text{ V}_{\text{AC}}$$

The secondary windings can be tapped at intervals which change the number of windings and proportionally change the secondary AC voltage. By moving “taps”, the number of windings changes with a corresponding change in voltage. This is the approach taken in most constant voltage rectifiers.

Rectifying Circuits

Bridge Circuits

Rectifiers are available for either single-phase or three-phase input power. Although single-phase rectifiers are available in half-wave (1 diode), center-tapped (2 diodes), and full-wave (4 diodes) bridges, the full-wave bridge is the standard most often used, as shown in Figure 4.5 (A,B,C,D).

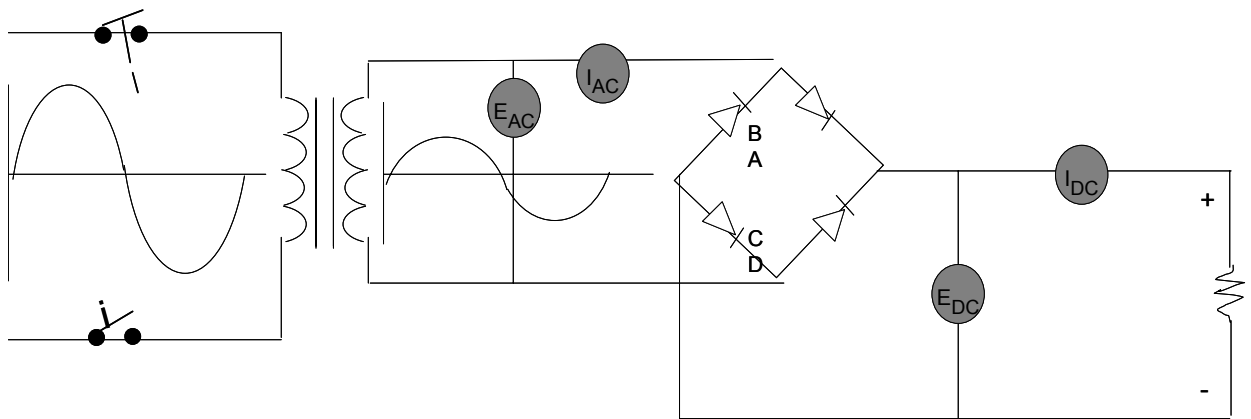


Figure 4.5 Single-Phase Bridge Rectifier Circuit

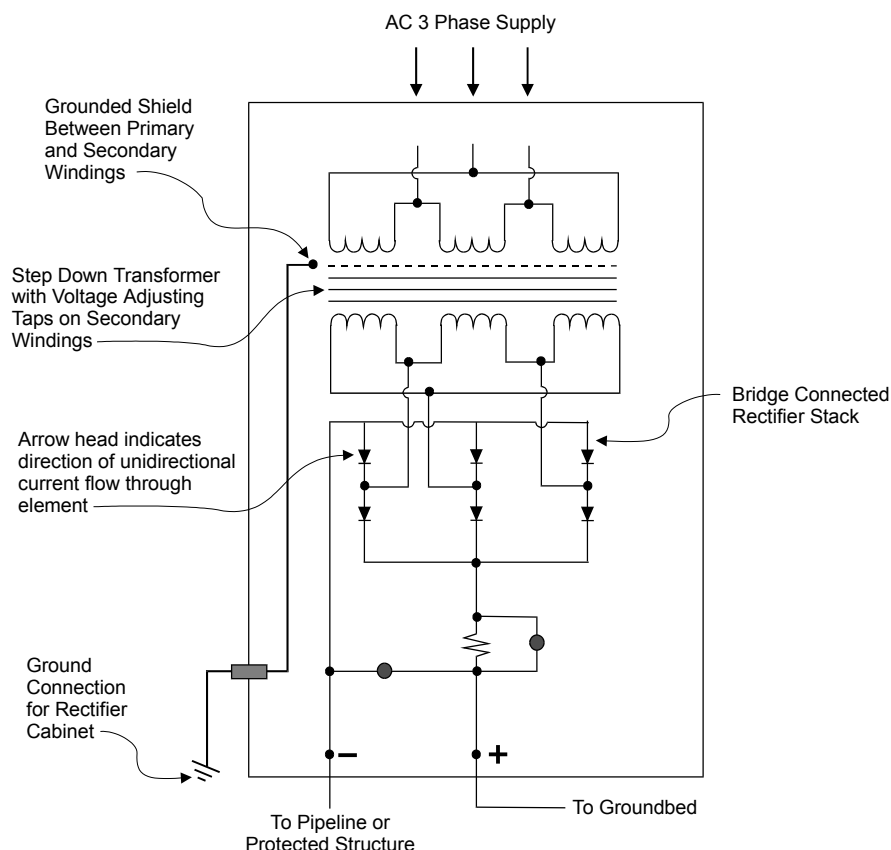


Figure 4.6 Three-Phase Bridge Rectifier Circuit

Three-phase rectifiers are available in wye (3 diodes) or full-wave (6 diodes) with full-wave bridges (shown in Figure 4.6) being the most commonly used. Three-phase units are more efficient than single-phase units, but the initial investment costs are higher. The theoretical maximum efficiency for a three-phase, full-wave bridge rectifier is 96.5% compared to 81% for a single-phase, full-wave bridge rectifier. The actual operating efficiency depends on the specific output of the unit. The type of power available and the economic comparison of overall costs are the primary considerations in selecting a single-phase or three-phase rectifier.¹

Modern rectifiers employ either selenium or silicon diodes to provide the rectifying action. Diodes are electrical devices that allow current to pass in one direction but block current in the opposite direction. A PN junction accomplishes this with a semiconductor boundary with one side of the junction doped with positive charge carriers and the other side doped with negative

¹ R. L. Bianchetti, ed., *Control of Pipeline Corrosion, Second ed.* (Houston, TX: NACE, 2001), p. 90, 166-173, 308-310, and 315-317.

charge carriers. If we apply a positive potential to the P or positive-doped semiconductor, the diode is forward biased and conduction can occur. However, if we apply a positive potential to the N junction or negative-doped semiconductor, the diode is reverse biased and current is blocked. In this manner, an AC voltage applied across a diode results in the diode alternating between being forward biased and conducting for one-half cycle and being reverse biased and blocking for the other half cycle. By proper interconnection of four diodes in the case of a single-phase rectifier, a complete AC current cycle can pass through the bridge, but with the positive portion of the cycle directed to the positive DC output terminal and the negative portion of the cycle directed to the negative DC output terminal. The result is full rectification of the complete AC cycle. However, this is not true DC in the sense that the signal output is completely constant, but rather a varying, single-directional output is produced.²

The rectification process is illustrated by the bridge circuit shown in Figure 4.7. The two AC input terminals to the rectifying bridge are I1 and I2. The two DC output terminals are O1 and O2. During the portion of the AC cycle when I1 becomes positive relative to I2, diodes 1 and 4 are forward biased (conducting). During this interval, the positive potential at I1 passes to output terminal O1, and the negative potential at I2 passes to output terminal O2. During the portion of the AC cycle when I1 becomes negative relative to I2, diodes 2 and 3 are forward biased (conducting). During this interval, the negative potential at I1 passes to output terminal O2, and the positive potential at I2 passes to output terminal O1. As indicated, the positive potentials always transfer to output terminal O1, and the negative potentials transfer to output terminal O2. Therefore, output terminal O1 is always positive relative to terminal O2. The top portion of Figure 4.8 shows the input signal between terminals I1 and I2, and the bottom portion of Figure 4.8 shows the resulting output signal between terminals O1 and O2.

² R. L. Bianchetti, ed., *Control of Pipeline Corrosion, Second ed.* (Houston, TX: NACE, 2001), p. 90, 166-173, 308-310, and 315-317.

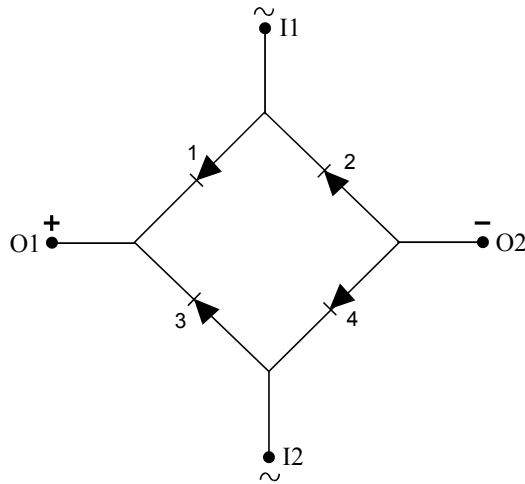


Figure 4.7 Single-Phase Diode Bridge

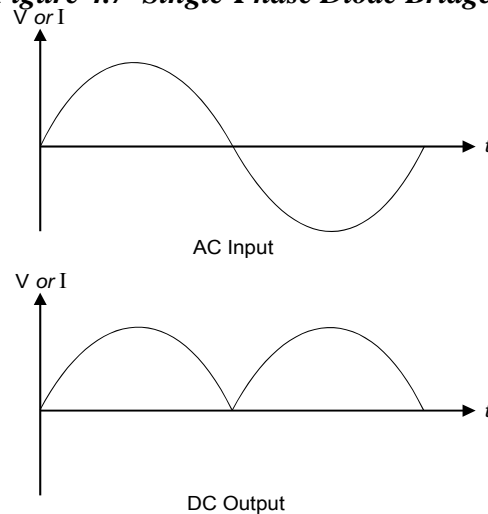


Figure 4.8 Input and Output Signals from Single-Phase Diode Bridge

Rectifying elements are made of either selenium coated plates or silicon diodes. In a selenium stack, steel, nickel, or aluminum plates are coated with selenium rectifier crystals. Plates are arranged in "stacks," with the number and size of plates being determined by the voltage and current output capacity of the rectifier. Significant facts about selenium stacks are:

- Selenium diodes are often called "self-healing"; that is, damaged areas become nonconductive and the stack continues to operate, however, the efficiency of the stack decreases.
- Selenium stacks can tolerate current overloads up to ten times rated capacity for a few minutes.

- Aging occurs due to heating resulting in reduced output voltage.
- Overheating occurs if the AC voltage exceeds the stack rating.
- Breakdown of the selenium coating and overheating due to transient voltages (e.g., lightning) can occur.
- Insulation breakdown of the insulating tube around the mounting stud due to transient voltages can occur.
- Corrosion due to salt, acids, hydrogen sulfide, or other chemicals can damage selenium stacks.
- Physical damage to the coating can occur due to overtightening or overheating due to undertightening of the contact washers during assembly.

Silicon diodes consist of a wafer sliced from a pure single crystal of silicon. The wafer is hermetically sealed inside a metal case with a threaded stud on one end and a wire connector on the other.

Silicon diodes are more efficient than selenium stacks and do not age.

The silicon diode must be attached to a heat sink since they heat up quickly.

Silicon diodes are more sensitive to current surges and can be quickly destroyed by any current overload. Diodes should have a high peak inverse voltage rating (1,000 V).

Silicon diodes fail completely rather than slowly like selenium stacks.

Although the standard transformer-rectifier is by far the most common power supply used for impressed current cathodic protection systems due to economics, variations of the standard transformer-rectifier are available such as silicon-controlled rectifiers, switching-mode rectifiers, and pulse-type rectifiers.

Center Tap Circuits

Full-wave rectification can be achieved with two diodes in a center tap configuration as shown in Figure 4.9 for single phase and a variation in Figure 4.10 for a three-phase wye connection.

In the single phase circuit, only one diode conducts during each AC cycle and produces a large ripple. This rectifier requires a larger transformer and adjustments by tapping the rectifier are more difficult as each leg needs to be balanced. This method is often used where the output is electronically controlled.

The three phase wye requires the largest iron core for the transformer to prevent DC saturation of the core from the DC ripple.

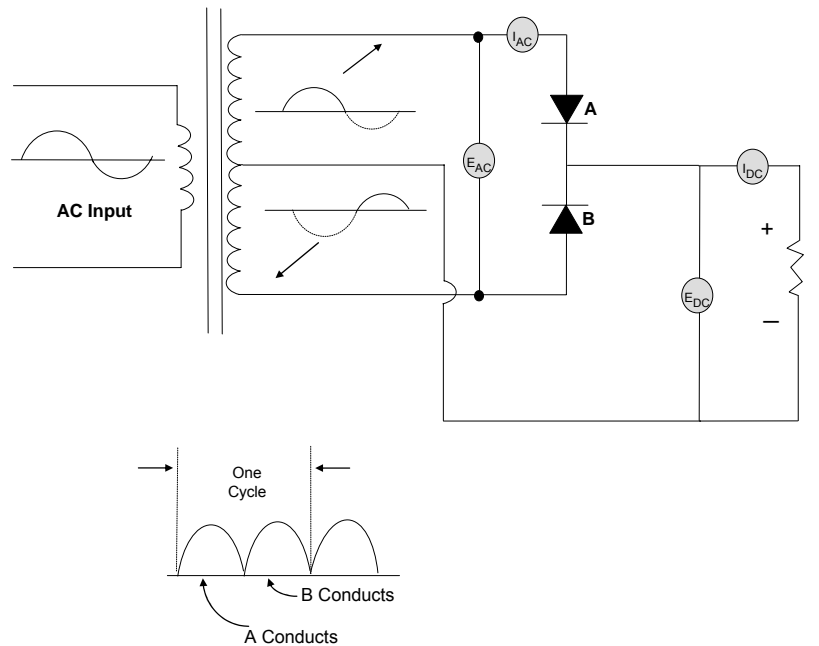


Figure 4.9 Single Phase Center Tap Rectifier Schematic

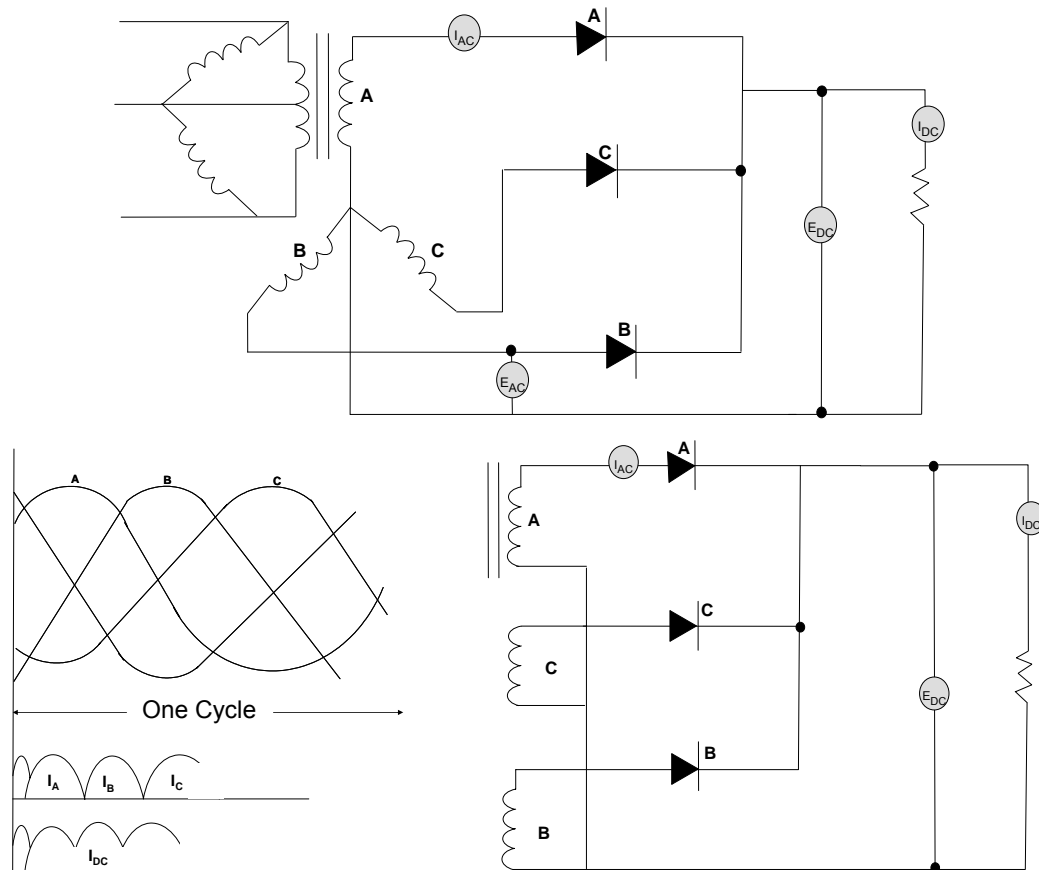


Figure 4.10 Three Phase Wye Rectifier Schematic

Silicon-Controlled Rectifiers (SCR)

Silicon-controlled rectifiers (SCR) are sometimes added to provide additional control of the rectification process for some types of cathodic protection rectifiers. SCRs are three-junction PN devices, as shown in the top of Figure 4.11. An SCR, much like a diode, is a rectifying device, which will permit current conduction in only one direction. However, unlike a diode, applying proper voltage polarity between the anode and cathode will not cause the SCR to conduct (fire). In order for the SCR to be forward biased and begin conducting, a positive potential (V_{AC}) must be applied between anode (P side) and cathode (N side), and a positive voltage pulse must also be applied between the gate and the cathode (V_{GC}) as seen in the center of Figure 4.11. At the instant the gate pulse is applied, the SCR fires and begins to conduct current from the anode to the cathode. Regardless of the gate current, the SCR continues to conduct until the applied voltage (V_{AC}) goes to zero and the current returns to zero.

If we apply an AC voltage across the SCR, we can control the output voltage waveform by controlling the timing for the gate pulse, which fires the SCR. For example, if the gate pulse arrives at the same time the applied voltage crossed the zero axis and begins to move in the positive direction, the SCR will conduct through a complete half cycle (180°) of the input waveform. If the gate pulse is delayed for one quarter of a cycle from the time the applied voltage crosses the zero axis and moves in the positive direction, one-half of the half cycle (90°) waveform will be allowed to pass. If the gate pulse is never applied, none of the half cycle waveform will pass (0°).

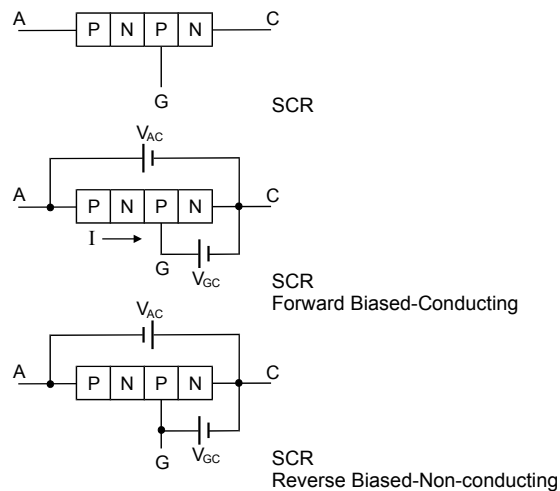


Figure 4.11 Silicon Controlled Rectifier (SCR)

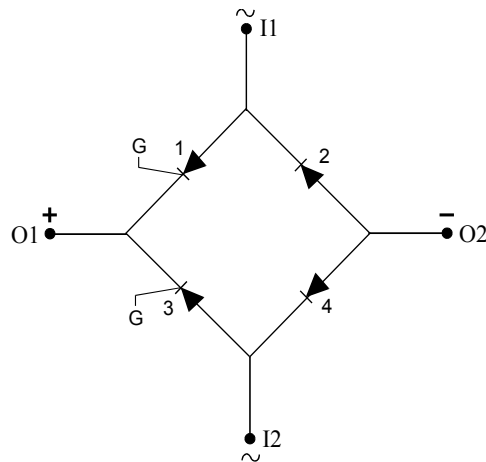


Figure 4.12 Single-Phase SCR Controlled Bridge

By replacing diodes 1 and 3 with SCRs in a full wave bridge circuit as shown in Figure 4.12, we can control the full-wave rectified output by controlling the timing of the gate pulses for the two SCRs. If the gate pulses are applied at the zero crossing of the input waveform (180° conduction angle), the output waveform is a fully rectified version of the input waveform, as shown in Figure 4.13. If we delay application of the gate pulse for one-third of the half-cycle (120° conduction angle), we block one-third of each half cycle at the output. The result is a reduction in the average DC voltage output. Therefore, by controlling the timing of the gate pulses we can continuously vary the level of the DC voltage output. However, the output waveform is not a continuous DC voltage, but rather a pulsing DC with ripple. The longer the control circuit delays the gate pulse, the greater the ripple in the output waveform will be. To improve efficiency and reduce ripple, manufacturers normally add filters to the output terminals.

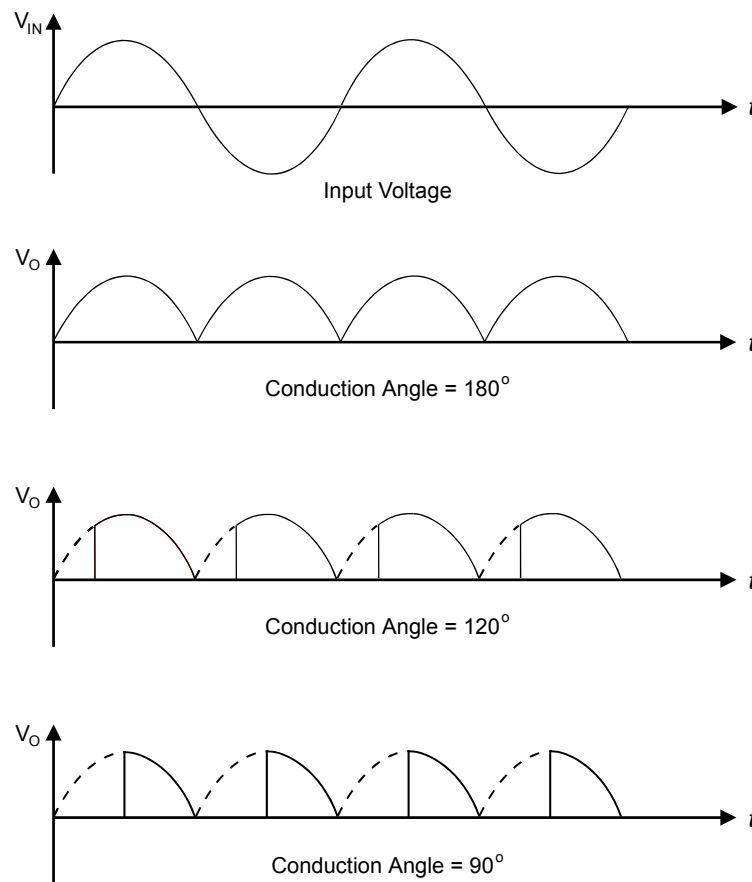


Figure 4.13 Full-Wave SCR Bridge Output Waveforms

The above explanation of the full-wave SCR-controlled rectifier operation assumes a pure resistance load at the output terminals. However, if the rectifier contains an output filter (energy storage), the SCRs may not be able to turn off when the input waveform crosses the zero axis due to the energy released from the filter. This condition is known as “latching” of the SCR. If we add a “free-wheeling” diode (see Figure 4.18) across the output, the SCRs can again turn off normally at the end of each half-cycle.

Switching-Mode Rectifiers

A different type of rectifier began to emerge in the late 1970s when switching-mode technology became commercially available. Rather than adjusting the output voltage level using a large, laminated steel core transformer, switching-mode rectifiers control the DC output voltage level by producing a series of high frequency (typically 50 to 500 kHz) DC pulses and adjusting the timing of DC pulses to produce the required output DC voltage level. Although switching-mode rectifiers use transformers for energy storage and for isolation of the output circuit, the transformer is a much smaller, high frequency, ferrite-core transformer. The block diagram for a typical switching-mode rectifier is shown in the bottom half of Figure 4-13. This diagram can be compared to the block diagram for a standard transformer/rectifier shown in the top of Figure 4.14.

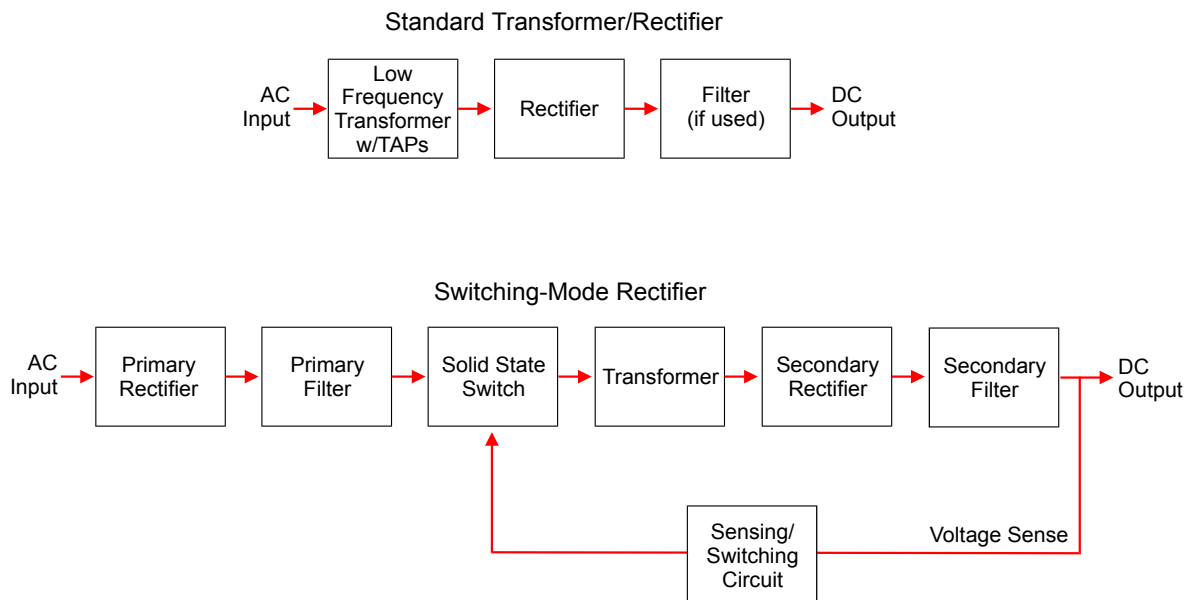


Figure 4.14 Block Diagrams for Switching-Mode and Standard Rectifiers

Source: Redrawn from Emerson Network Power, Switching Power Supplies, <http://www.emersonnetworkpower-medical.com> (January 7, 2004).

As indicated in Figure 4.14, the switching-mode rectifier first converts and filters the input AC voltage to a DC voltage. The solid state switch next converts the DC to high frequency DC pulses. The DC pulses are fed through a high frequency transformer to isolate the output. Because the high frequency signal contains significant noise (positive and negative spikes), it is necessary to provide secondary rectification of the signal along with filtering. Finally, the sensing/ switching control circuit provides feedback control to the solid state switch to control the “on” and “off” timing (pulse width) of the switch. Therefore, using pulse width control, the magnitude of the output voltage is adjusted and controlled.³

The primary advantages of a switching-mode rectifier over a standard transformer/ rectifier are:

- Small size and weight
- Output voltage regulation
- High efficiency at low rated output
- Current-limiting features available
- Modular design for ease of repair
- Multiple modes of operation possible (constant voltage, constant potential, constant current, IR-free constant potential)

The disadvantages are:

- Can be a significant source of high frequency noise (EMI/RFI)
- Lower reliability due to number of components
- Prone to higher ripple (more filtering required)
- Repair of individual modules not practical

Pulse Rectifier

Pulse rectifiers supply current in a cyclic fashion. The current is delivered as a high frequency (1,000 to 5,000 pulses per second) at a relatively high voltage but usually at a low duty cycle (15%). Adjustment of the output is a combination of varying the frequency and adjusting capacitors that in turn set the duty cycle. As a result they have a high noise level for a short distance from the installation. The primary use of these rectifiers is on well casings. These rectifiers are intended to optimize current distribution and minimize interference.

³ Lambda Power, Switch-mode Power Supplies,
http://www.lambdapower.com/ftp/linera_versus_switching.pdf (January 7, 2004)

Operational Modes

The common rectifier operation modes include:

- Constant Voltage
- Constant Current
- Constant Potential

Constant Voltage

In this type of rectifier, the output voltage is adjusted by changing the secondary transformer taps. The output of the rectifier is dependent on the external resistance of the anode-soil-structure circuit. This type of control is useful where the external circuit resistance does not change appreciably. Figure 4.15 shows a schematic diagram of a typical voltage control rectifier.

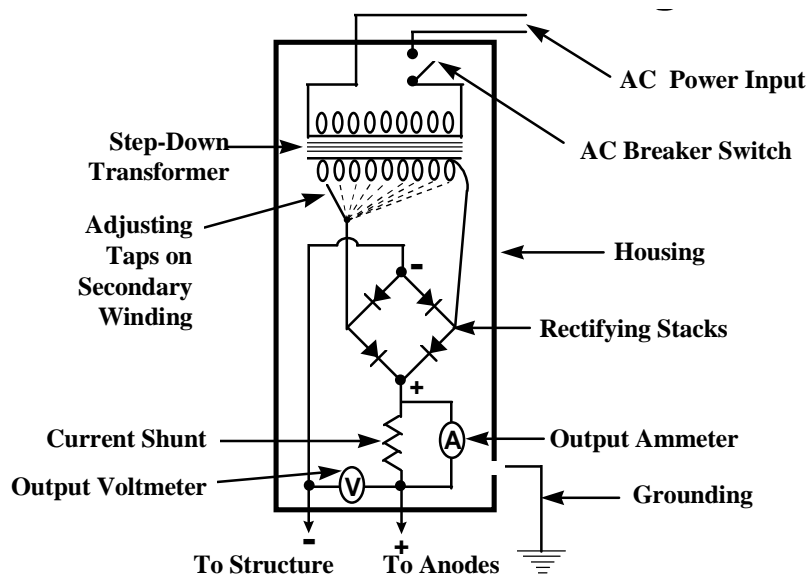


Figure 4.15 Constant Voltage Rectifier Schematic – Single Phase

Constant Current

In this type of rectifier, the output current is maintained at a constant preset value. If the external resistance changes, the rectifier output voltage is increased or decreased to maintain the preset value. An external reference electrode is not used in this type of rectifier. Figure 4.16 shows a schematic of a typical constant current control rectifier using a saturable reactor. A constant current rectifier can also be achieved using silicon-controlled diodes.

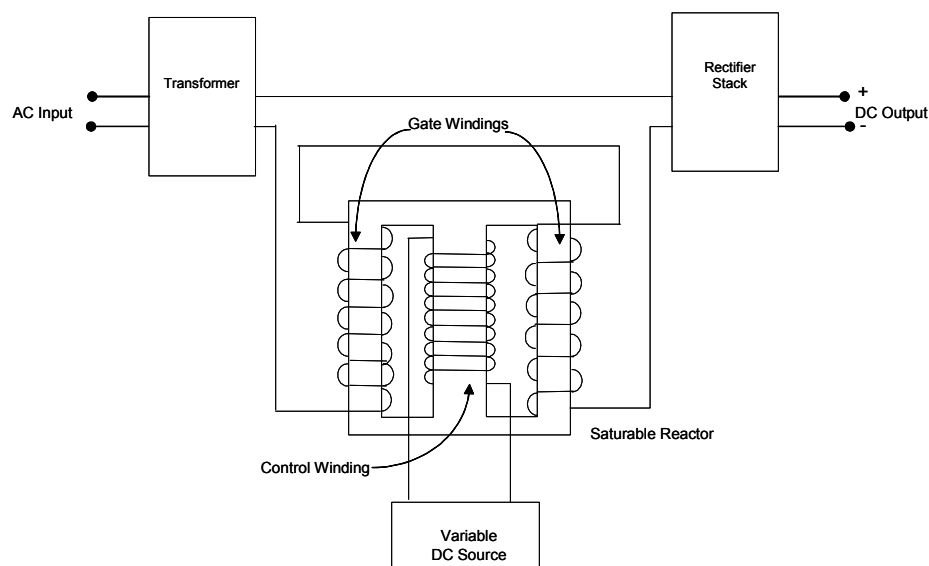
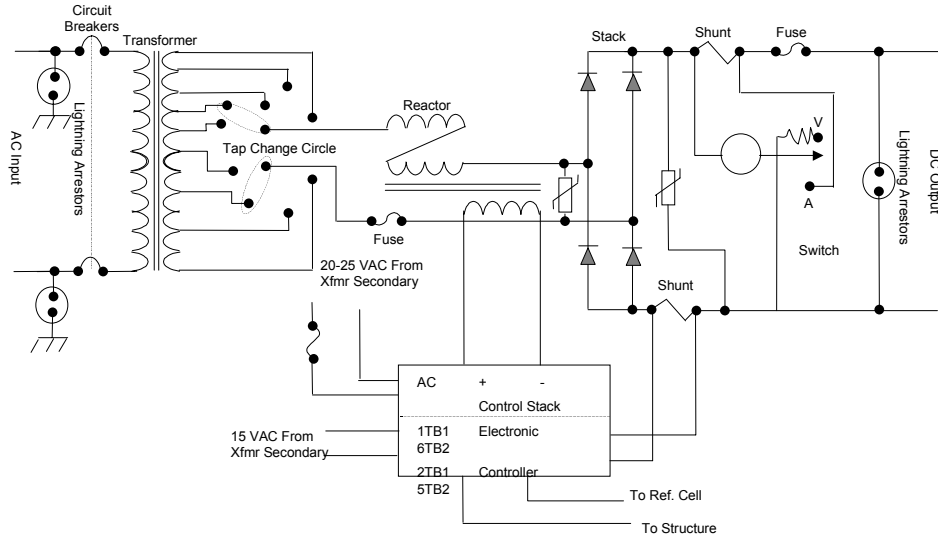


Figure 4.16 Constant Current Rectifier Schematic

Constant Potential

The output current of constant potential rectifiers is controlled by a preset structure-to-electrolyte (or structure-to-water) potential. The rectifier constantly monitors an external structure-to-electrolyte potential and compares it to the preset value. If the structure-to-electrolyte potential changes from the preset value, the rectifier current either increases or decreases current output to bring the potential back to its preset value. This type of rectifier is useful where external conditions vary, in particular, the resistivity of the electrolyte that can cause large changes in corrosion protection requirements. For this system to work, a stable reference electrode must be buried or immersed in the environment to monitor the structure-to-electrolyte potential. Potential control rectifiers can be controlled by either saturable core reactors or silicon controlled rectifiers (SCR). Figure 4.17 shows a schematic of a typical voltage control rectifier using a saturable reactor and Figure 4.18 shows a potential control rectifier with SCR control. These rectifiers should be manufactured with a current limiting circuit in the event of a loss of reference cell input signal.



Single Phase Reactor Controlled Auto-Volt

Figure 4.17 Constant Potential Rectifier Schematic

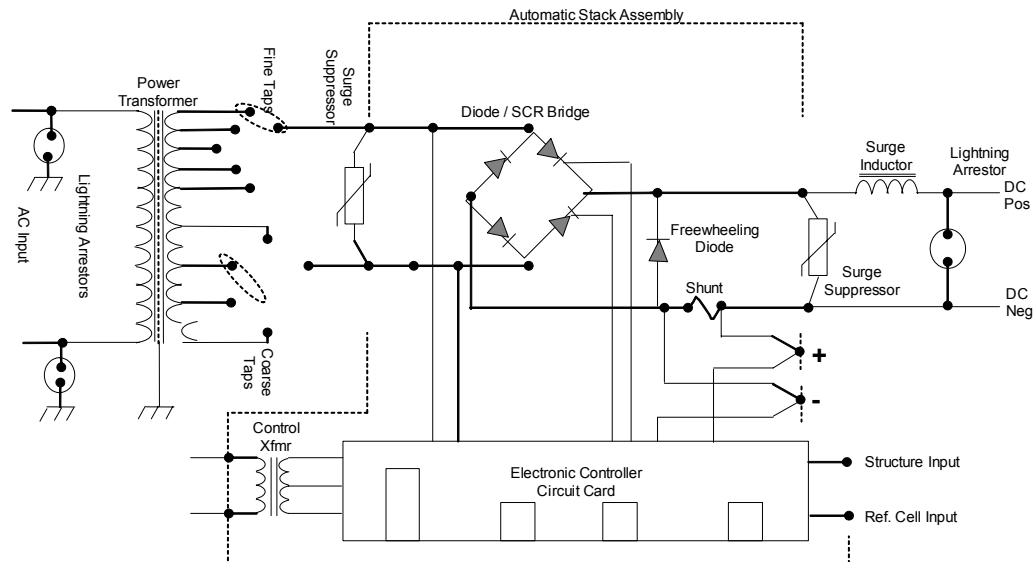


Figure 4.18 Constant Potential Rectifier Schematic - SCR

Other Rectifier Components

Filters

Efficiency filters are used to decrease the AC ripple of the DC output, which decreases the operating cost of the rectifier. Filters are most often used on

single-phase bridge and center tap rectifiers. Filters consist of chokes, capacitors, or a combination of capacitors and chokes.

Surge Protection

Surge protection is used to protect the rectifier from lightning.

Interrupters

Built-in interrupters can be supplied with the rectifier to allow cycling the unit on and off for testing purposes.

Warning Devices and Signal Lights

These are used to alert personnel to operating malfunctions of the unit. They will not provide information on irregularities with the cathodic protection system other than what is occurring within the rectifier itself.

Remote Monitoring

Devices can be installed to monitor current, voltage, and structure potential from a remote location. Some of these devices can be used to control the output.

Adjustments of AC and DC

As described above constant voltage rectifiers are usually adjusted by changing the transformer tap settings. These adjustments change the AC voltage supplied to the rectifier stacks. The adjustment taps are found on the front panel of the unit and consist of shorting bars for coarse and fine adjustment. The rectifier **MUST** be turned off at the breaker before any taps are changed. A lock out/tag out procedure is also recommended. Changes should be made one step at a time.

The general procedure to change taps is to increase the Fine tap one setting making certain that the connections are tight. Turn on the unit and measure the DC output voltage and current. If not satisfactory, increase the Fine taps again and repeat the process. When the Fine taps have reached the maximum, lower it to the first setting and increase the Coarse taps one setting. Continue in this manner until the desired output is reached. To lower the output, the reverse procedure is used except that a major reduction may be in order if the reason to reduce the taps is because the circuit breaker tripped.

Potential control and constant current rectifiers are controlled using a potentiometer adjustment found on the controlling circuit board. On potential control rectifiers, this adjustment controls the structure-to-reference potential, which controls the output voltage and current. Transformer tap setting bars are often also found on potential control and constant current rectifiers as another control on the DC voltage.

Other Power Sources

Other sources of power are available where AC power is not readily accessible.

Engine Generator Sets

Engine generator sets consist of a fuel-powered engine that drives a generator to provide the AC for the rectifier (see Figure 4.19). The pipeline or a nearby source could supply the fuel. DC generators can be considered but usually require high maintenance.

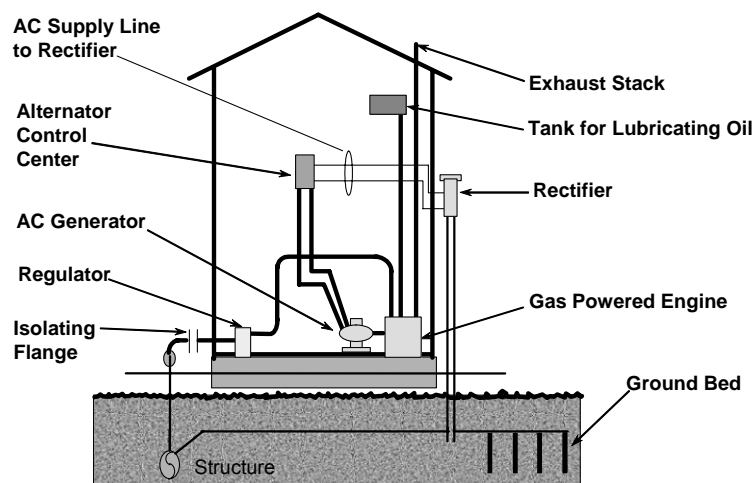


Figure 4.19 Engine-Generator CP Installation

Thermoelectric Generators

Another alternative energy power supply available for cathodic protection applications is the thermoelectric generator (TEG) (Figure 4.20). Thermoelectric generators convert heat energy directly into electrical energy. A clean fuel such as natural gas or propane is required. They are a relatively low power (wattage) unit and must operate near their optimum load resistance to realize the rated output.

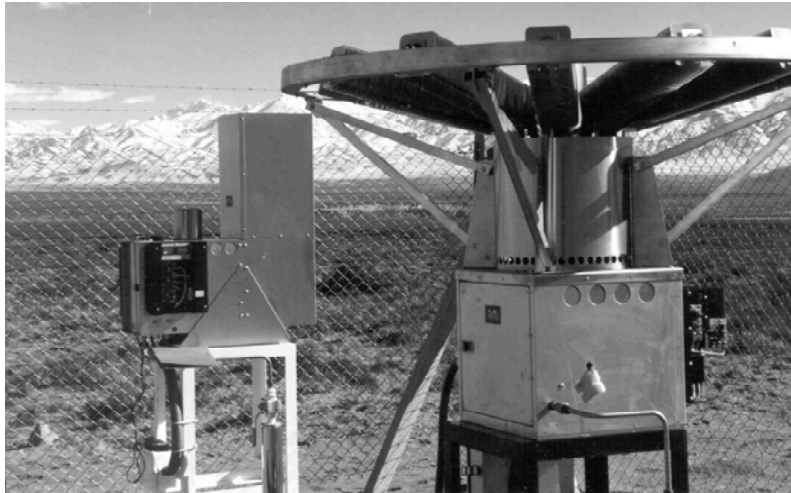


Figure 4.20 Thermoelectric Generator for CP

This power supply uses the Seebeck effect to generate small potentials across a dissimilar metal junction. Thomas Seebeck discovered that if a junction made up of two different metals is heated on one side and cooled on the other, a potential difference develops across the junction and charge flow will occur. Thermoelectric generators require only three primary components: a heat source, a thermopile, and cooling fins.⁴

Modern thermoelectric generators employ semiconducting PN junctions rather than dissimilar metal junctions. A burner applies heat to one side of the PN junction while a heat transfer system cools the other side of the junction. The thermoelectric couple is a low voltage, high current power source. Although the potential generated across an individual PN junction is very small, approximately 90 mV, the manufacturer increases the output voltage level by connecting many junctions in series modules (thermopiles). They can also connect several thermopiles in parallel to increase the current output. Burning of a fuel such as propane, butane, or natural gas produces the heat for one side of the junction. Temperatures on the hot side of the junction are approximately 535°C (1,000°F), while a heat transfer and elimination system maintains the temperatures of the cool side at about 165°C (325°F). The power produced by the unit is a direct function of the temperature difference across the junction. Some semi-conducting designs cannot be operated in the no-load condition since current output is necessary to cool the PN junction.^{5,6}

⁴Donald G. Fink and H. Wayne Beaty, ed., *Standard Handbook for Electrical Engineers*, Eleventh ed. (New York, NY: McGraw-Hill, 1978), p. 2-3, and 11-71 to 11-81.

⁵CP 4—Cathodic Protection Specialist Course Manual (Houston, TX: NACE, 2002), p. 1:25-1:27, 3:4-3:11, 3:18-3:33, and 8:34-8:35.

Since thermoelectric generators use no moving parts, no significant maintenance is required. Normally, only annual cleaning or replacing the fuel filter and fuel orifice is required. Units are available with output voltages of up to 48 V and power ratings of over 500 W. Manufacturers design and rate thermoelectric generators on a power output basis. For efficient application, TEGs should be matched to a specific load resistance (usually 1 Ω). The operator can make limited adjustment to the current output by adjusting the input fuel supply; however, a variable power resistor in series with the output or other type of voltage control is required to adjust output.⁷

Solar Power Supplies

Figure 4.21 shows a solar power supply consisting of a solar panel, a charge controller, and a battery system. Specially designed doped silicon semiconductors, which are photosensitive, convert solar energy to electrical energy. These semiconducting devices (photovoltaic cells) produce a voltage by absorbing energy from light photons striking the semiconductor and freeing electrons within the semiconductor. The conversion efficiencies for silicon-based photovoltaic cells are in the range of 8 to 14%. Research and development teams continue to improve the conversion efficiency and lower the production costs for photovoltaic technology. Recent innovations in thin film modules using a fine layer of copper indium diselenide (CuInSe_2 or CIS) on a glass backing can potentially lower production costs significantly in the future. Research is currently under way combining the amorphous silicon with CIS producing a double layer, thin film photovoltaic cell with a conversion efficiency of 15.6%.^{8,9,10}

⁶R. L. Bianchetti, ed., *Control of Pipeline Corrosion*, Second ed. (Houston, TX: NACE, 2001), p. 90, 166-173, 308-310, and 315-317.

⁷Global Thermoelectric, *8550 Thermoelectric Generator Operating Manual* (Calgary, Alberta, Canada: Global Thermoelectric, 2002).

⁸Shell Solar, *Solar Panels*, <http://www.shell.com> (November 11, 2003).

⁹Siemens, *Solar Panels*, <http://siemenssolar.co.uk> (November 11, 2003).

¹⁰Go Solar Company, *Solar Panels*, <http://www.solarexpert.com> (November 11, 2003).

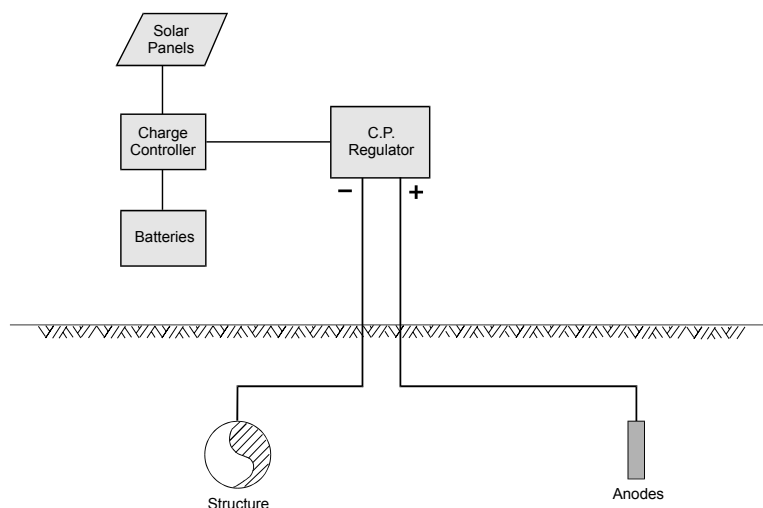


Figure 4.21 Solar Power Supply System for CP

A single photovoltaic cell produces a very small voltage and current. By connecting a number of cells in series, the output voltage available increases or by connecting cells in parallel, the current output available increases. Therefore, manufacturers produce standard solar panels consisting of a number of photovoltaic cells connected in a series/parallel arrangement to produce a specific output voltage and current. Solar panels are available in output voltages of 6, 12, and 24 V with power outputs ranging from 5 to 160 W. Designers can also connect solar panels in series or parallel, as necessary, to produce an even larger output current or voltage.¹¹

A backup battery system is necessary with a solar power supply to produce the required current output when solar energy is unavailable (night and overcast days). The designer must size the solar panel to produce the required current output plus additional current to charge the battery system when solar energy is available. Whenever the solar energy available is insufficient, the battery system supplies the current required for cathodic protection. A charge controller is an electronic monitor to determine the state-of-charge of the battery allowing charging current to the batteries when needed and preventing overcharging of the batteries.

Wind-Driven Generators

If a sufficient, steady source of wind is available, wind-driven generators are another possible alternate energy source for cathodic protection. These DC

¹¹Go Solar Company, *Solar Panels*, <http://www.solarexpert.com> (November 11, 2003).

generators generally begin producing useable current outputs at wind speeds of about 16 km/h (10 mph) with maximum output achieved at speeds of 40 to 55 km/h (25 to 35 mph). Since the output varies with wind speed, a battery system is required not only as a backup when the wind is flat, but also to provide a constant DC output for the cathodic protection system. The generator output charges a battery system, and the battery system supplies the output cathodic protection current (Figure 4.22).

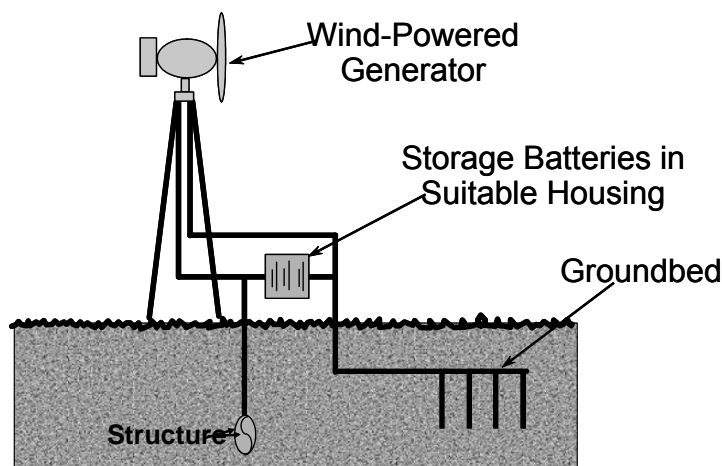


Figure 4.22 Wind-Driven Generators for CP

Due to the high maintenance requirements of wind-driven generators, these power sources are not as popular especially with the continuing development of other more cost competitive alternate power sources. Wind-driven generators are available in 400 to 3,000 W sizes with voltage outputs ranging from 12 to 240 V.¹²

Batteries

If the current requirement for a specific cathodic protection system is relatively small, it is possible to use batteries to supply the output current. A small, isolated, well coated structure in a high resistivity environment might use a battery power supply, perhaps in conjunction with galvanic anodes, to supply the required current output. Batteries used in cathodic protection applications should be deep-cycle batteries designed for many charge/discharge cycles.

¹²JATS Alternative Power Company, *Wind-driven Generators*, <http://www.jatsgreenpower.com/wind-power.html> (November 11, 2003).

Battery manufacturers rate batteries in terms of ampere-hour capacity. Simply stated, this is the amount of current in amperes a battery can supply for a specific time interval, hours. Temperature can have a significant effect on output capacity of batteries, especially lead-acid batteries. At a temperature of -19°C (0°F), the capacity of a lead-acid battery drops to about 50% of rated output. A successfully designed battery system must be able to supply the output current required for a relatively long time before battery replacement is necessary.¹³

Whether batteries are the primary power supply or a backup for another primary power source, regular maintenance is required to ensure the batteries operate successfully over the long term. If batteries are the primary power supply, they must be replaced with new fully charged batteries on a regular schedule. Due to the maintenance and regular replacement schedule requirement, the cost associated with battery systems can be relatively high.

Fuel Cells

An emerging alternative energy power supply is the fuel cell and although not presently in use for cathodic protection it can possibly be a DC power source for the future. NASA originally developed this technology for the space program but only recently have commercial applications exploited the technology. A fuel cell requires three parts: an anode, a cathode, and an electrolyte. The fuel, hydrogen, passes through a porous anode catalyst, which causes the hydrogen to release its electron into the metal electrode. The hydrogen ion moves through the electrolyte where it combines with oxygen gas passing through the porous cathode and the electrons from the anode to produce heat and water.¹⁴

Depending on the specific design of the fuel cell, fuel may be in many forms including gaseous hydrogen, methane, propane, and even gasoline. Air from the atmosphere usually provides the oxygen required at the cathode. The fuel cell produces current electrochemically; therefore, no moving parts are required, and maintenance is minimal. Fuel cells are more efficient than any other form of energy conversion and free of polluting emissions.

¹³Go Solar Company, *Solar Panels*, <http://www.solarexpert.com> (November 11, 2003).

¹⁴Online Fuel Cell Information Center, *Fuel Cells*, <http://www.fuelcells.org> (November 11, 2003).

Rectifier Testing

- **CAUTION:** Only qualified personnel are to test and work on a rectifier. Safety is of the utmost importance when working on an electrical device.
- Note the precautions in Chapter 5–Safety.
- Determine if the rectifier or any associated electrical equipment is in an electrically hazardous area. Do not open any explosion-proof junction boxes unless otherwise qualified and then only if the circuits are turned off and locked out/tagged out.
- Do not work on or remove any rectifier component without first turning the upstream power off and locking/tagging out (Figure 4.23).
- When first approaching the rectifier confirm that the case is not electrically “hot” either by taking an AC voltage-to-ground measurement or with a voltage alert device.
- On first opening the rectifier identify any exposed terminals that will have a voltage and take measures to protect yourself from them.



Figure 4.23 Typical Lock Out / Tag Out Kit

It is important to ensure that the power source in an impressed current system, such as a rectifier, remains operational and that the cathodic protection system is connected with proper polarity.

The negative (–) terminal of the power source must be connected to the structure and the positive (+) terminal must be connected to the anode bed (see Figure 4.24).

The proper connection of a rectifier is CRITICAL and if done improperly can result in catastrophic damage to the structure that is supposed to be protected, resulting in loss of product, structural damage, property damage, environmental damage, or loss of life.

Often the cathodic protection cables are either not identified or are incorrectly identified. It is therefore mandatory to verify the proper connection polarity. This can be accomplished by measuring the structure-to-electrolyte potential near the power source both before and after the source is activated. A shift in potential in the electronegative direction with the power source energized, confirms the correct polarity. For this test the cable connected to the negative terminal of the rectifier should not be used as the test lead for the structure-to-electrolyte potential measurement.

When connecting a rectifier to an AC power supply, the AC supply circuit should be dedicated and separately fused. The rectifier should never share an AC circuit with normally interruptible facilities such as lighting and pumps.

The voltage and current output of the power source should be monitored regularly to ensure that the unit remains operational. Basic rectifier operational data includes:

- AC input voltage
- DC output voltage and DC output current
- Tap settings and/or potential set point (if constant potential) or current set point (if constant current)
- Anode-to-structure resistance.

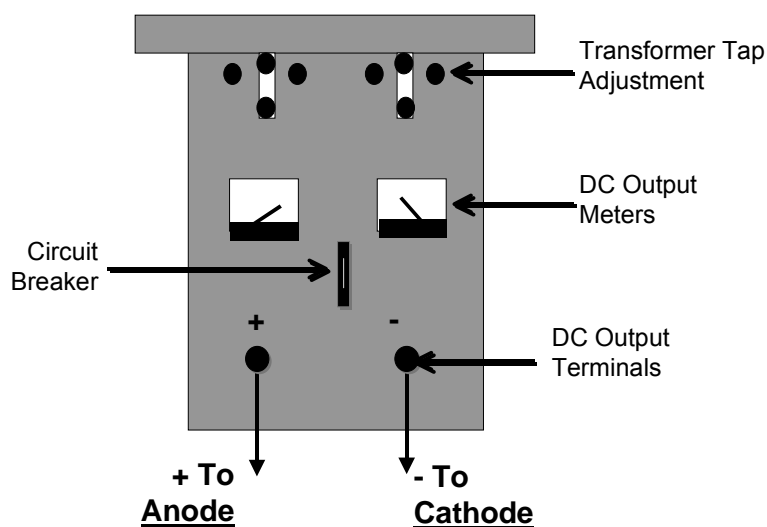


Figure 4.24 Typical Rectifier Connections

Output Problems

A good maintenance program can often detect potential rectifier failures beforehand allowing scheduled repair before an actual outage. Even with the best of maintenance programs, however, failures do occur. Often basic step-by-step troubleshooting techniques can determine the cause of the outage. For the following discussions, only standard single-phase, manual adjustment type rectifiers are considered.

When checking rectifier outputs on a routine basis, there are four basic cases of symptoms requiring investigation: (1) zero current and voltage outputs, (2) zero current output with unchanged output voltage, (3) significant current change with unchanged voltage, or (4) significant changes in both voltage and current outputs.

Zero Current and Voltage Outputs

For the case of zero output for both current and voltage, either there is no input power to the unit or an open circuit within the rectifier is indicated. First, determine if input AC voltage is present. If not, the problem is external to the rectifier. If AC voltage is present at the input terminals, an open circuit exists within the rectifier. However, the open circuit may be due to a tripped circuit breaker at the rectifier input.

The component causing the open circuit can be located by realizing that the rectifier voltage must exist across the open circuit element. If it is determined that the input circuit breaker has tripped, a high current or overload has

occurred. This high current could have been a temporary problem, perhaps due to a lightning surge, or a permanent short circuit. The best method of proceeding is to reduce the voltage output tap to a low level and reset the circuit breaker. If the circuit breaker does not trip again, the problem was probably temporary and full output voltage can be restored. If the circuit breaker does trip, a permanent short circuit is indicated.

The sequence of short circuit location based on a circuit breaker tripping is shown in Figure 4.25.

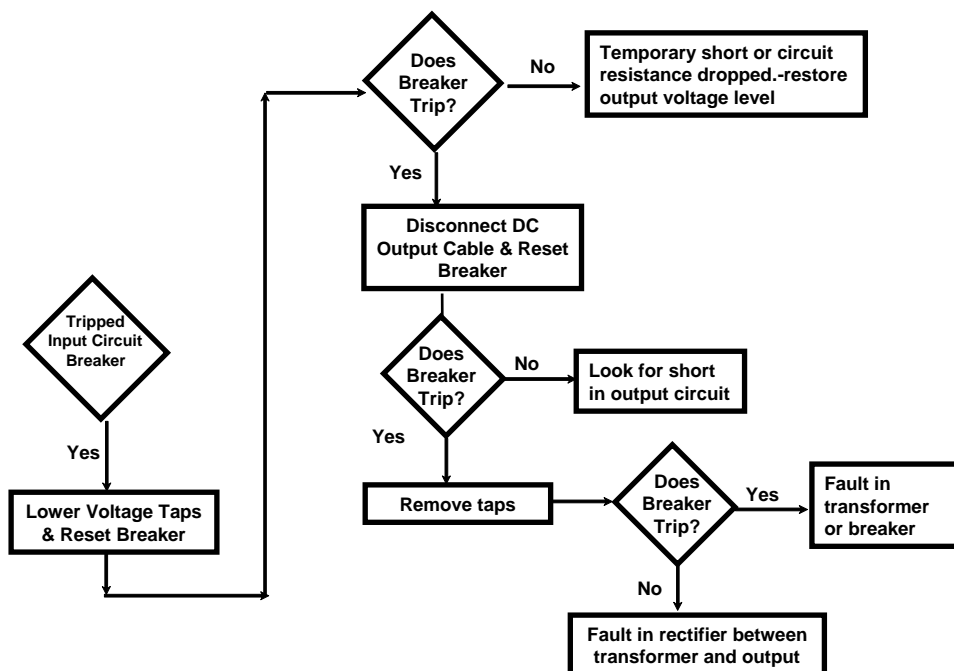


Figure 4.25 Locating a Short Circuit in a Rectifier Circuit Based on a Circuit Breaker Tripping

To determine if the short circuit is external to the rectifier, turn off the AC power supply, disconnect one of the DC output connection leads and reset the breaker. If the short circuit is external to the rectifier, the circuit breaker will not trip. If the short circuit is internal to the rectifier, the circuit breaker will again trip. Next, the best approach involves isolating the problem to a particular section of the rectifier by beginning at the input terminals and adding one component at a time to the circuit until the circuit breaker trips. The short circuit must be the last component connected when the circuit breaker trips. For example, the transformer can be connected to the input circuit breaker with the tap adjustment bars removed.

Zero Current Output with Unchanged Voltage Output

If the DC voltage output of the rectifier is relatively unchanged but the current output is zero, an open output circuit is indicated. This could be caused by:

- Open fuse in the output circuit. If an open fuse in the output circuit is found, either a high temporary current surge or a short exists (or has existed) in the output circuit.
- Faulty connections.
- An open positive or negative lead cables.
- Failed anodes.

Significant Current Change with Unchanged Voltage

If the DC current output significantly changes with no change in the output voltage, the output circuit resistance has changed. If the current output has significantly increased, a lower circuit resistance is indicated. This could be due to system additions, shorts to other underground structures, or major coating damage. If the current output significantly decreased, a higher circuit resistance is indicated. Some of the possible causes might include installation of inline isolators, anode deterioration, discontinuity due to disconnection of system component, or gas blockage. Seasonal variations in soil conditions, such as drying or frost, can also increase the current resistance.

Significant Changes in Both Voltage and Current Outputs

Sometimes both the voltage and current outputs will decrease significantly. If the voltage and current outputs are approximately one-half of the normal values, the most probable cause is partial failure of the rectifier stacks ("half waving"). If the rectifier stacks are found to be operating properly, the transformer should be investigated for possible winding-to-winding shorts.

The existing rectifier operational data should be compared to prior data from when the rectifier was known to be operating properly. If abnormal data is obtained, then troubleshooting procedures need to be used.

If the anode-to-structure resistance is normal, then the problem is with the rectifier.

If the anode-to-structure resistance is not normal, the problem could be outside the rectifier.

Open circuit and short circuit failure modes can occur on all impressed current systems. Usually a short circuit condition will cause either the rectifier breaker

or AC supply breaker to trip. In many instances, the power source fuses are also blown. The short circuit can appear either within the rectifier or external to the power supply.

The following conditions can cause internal short circuits:

- Failed diode(s)
- Contact in transformer windings
- Contact between positive circuit and the rectifier cabinet or negative circuit
- Spark-gap type lightning arrestors failed in the shorted condition

External short circuits can occur due to any metallic contact between the positive and negative circuits. Inadvertent contact between the anode or its low resistivity backfill and the structure is the most common type of external short circuit.

When confronted with a possible short circuit, disconnect all external positive and negative cables at the rectifier before re-energizing the rectifier. If the rectifier operates normally upon re-energizing, then the short is external to the unit, providing the short reappears when the cables are reconnected. Some rectifier units can be operated in the shorted condition when on the lowest AC tap setting. This facilitates troubleshooting to find the defective component. A pipe or cable locator connected between the positive and negative cables at the rectifier can also be used to pinpoint an external short circuit. Disconnecting the components in sequence starting at the output of the unit and working back toward the transformer is a relatively convenient method of locating the shorted component.

Open circuits can appear within the power source or external to it. The open circuit condition is characterized by a zero current output. If the open circuit is external to the rectifier then the voltage output will appear at the terminals of the rectifier. If the open circuit is internal, then the voltage will appear across the internal component with open circuit. Common causes of internal open circuits include the following:

- Failed diode(s)
- Broken cables
- Open connections
- Failed or weak breaker
- Blown fuse(s)

External open circuits generally involve broken or corroded cables, though, on occasion, the groundbed may be consumed.

Circuit Diagrams

Each rectifier should be supplied with its own specific circuit diagram that can be consulted to establish the electronic configuration of the unit. This is a code requirement in some areas.

Electrical Damage

Note that testing, using visual inspection must be performed with the rectifier off and AC power disconnected and locked out.

Electrical damage, such as from lightning or power surges, might be diagnosed by looking at and smelling the rectifier components. Electrical damage often shows as burnt, melted, or charred marks or the smell of burnt insulation may be present. If any of these are observed, electrical tests using a voltmeter and ohmmeter should be performed to see if the component is functioning. Electrically overstressed components will be hot to the touch.

Efficiency Test

The efficiency of a rectifier is calculated with a watt-hour meter and the following formula:

$$\text{Percent Efficiency} = \frac{\text{DC Power Out}}{\text{AC Power In}} \times 100 \quad \text{Eq. 4-2}$$

For example, calculate the efficiency of a rectifier with a DC output of 10 V 25 A DC if the watt meter reads 300 W.

$$\text{DC power out (watts)} = V_{\text{DC}} \times I_{\text{DC}} \quad \text{Eq. 4-3}$$

$$\text{Percent Efficiency} = \frac{10 \text{ v} \times 25 \text{ A}}{300 \text{ W}} \times 100$$

$$\text{Percent efficiency} = 83.3\%$$

If a watt-hour meter is used to determine the input power, the following formula is used:

$$AC \text{ Input Power} = \frac{3,600 K N}{T} \quad \text{Eq. 4-4}$$

where

K = meter constant (shown on face of meter)

N = number of revolutions of the disk (observe for 60 seconds minimum)

T = time in seconds of observation

If the efficiency is below what is expected or DC output voltage is about half that expected, the following can be responsible:

- Input voltage is too low for the rectifier rating
- Input voltage may be lower than it should be
- Half the stacks or plates are open-circuited making the unit operate as a half wave rather than a full-wave rectifier
- Badly aged stacks
- In a 3-phase unit:
 - One phase may be open-circuited
 - One phase may have stacks that are more aged than the others

Filters

Filters are used to improve efficiency and for noise interference control. They consist of capacitors and chokes. If the choke is suspected to be defective, it can be removed from the circuit with a heavy jumper placed across the choke leads.

Capacitors usually fail by shorting. The capacitors should be fused. If the fuse is blown, replace it and turn on the rectifier. If the fuse blows again, the capacitor is defective and should be replaced.

Detection of Cable Breaks

Wire connections within the rectifier can become disconnected or loose (e.g., broken solder joint, burned connection, pulled spade lug). These can be checked with a multimeter or gentle pull at the connection. Note: Turn off and lock out rectifier before testing.

Broken cables outside the rectifier are also a possibility. Causes of external cable breaks include: construction damage, broken bond connection to the structure, broken anode connection, or broken anode wire due to exposure of the metallic wire to the electrolyte at a fault in the insulation.

Testing Transformers

If AC voltage is present to the primary but not the secondary, check to see whether there is an audible hum coming from the transformer. If so, the primary is operating, but the secondary is probably open. Check the above conclusions by electrically isolating the transformer and checking the DC resistance of the windings with an ohmmeter. The secondary should have generally less than one (1) Ω resistance while the primary should have 1 to 10 Ω resistance.

If either value is high, the winding is effectively an open circuit and the transformer will have to be replaced.

Use an AC voltmeter to see if voltage is applied to the stacks. If AC voltage is present, the stacks may be open circuited and should be checked with an ohmmeter. Check the leads between stacks if multiple stacks are used. On silicon stacks, remove each diode and check individually with a diode checker for forward and reverse bias. A bad silicon diode is either open or shorted.

If there is no output voltage or current, the breaker or fuse might be blown. Reduce the output slightly if due to a steady overload. Check for a possible short circuit in some component. Isolate the component and replace or repair.

If the breaker trips occasionally for an unknown reason, the problem could be:

- Temporary overload due to soil moisture changes
- Line voltage surges or wrong line voltage connections
- Intermittent short circuits. Isolate the component. Check for loose connections or brackets. (Check with ohmmeter while moving components – with POWER OFF.)
- Thermal breaker may be affected by sun's heat – install shield or shade.

No AC line voltage. Check with voltmeter. Check the service to the rectifier or check for a:

- Open circuit in some component or connection
- Defective meters or meter switches
- Defective transformer

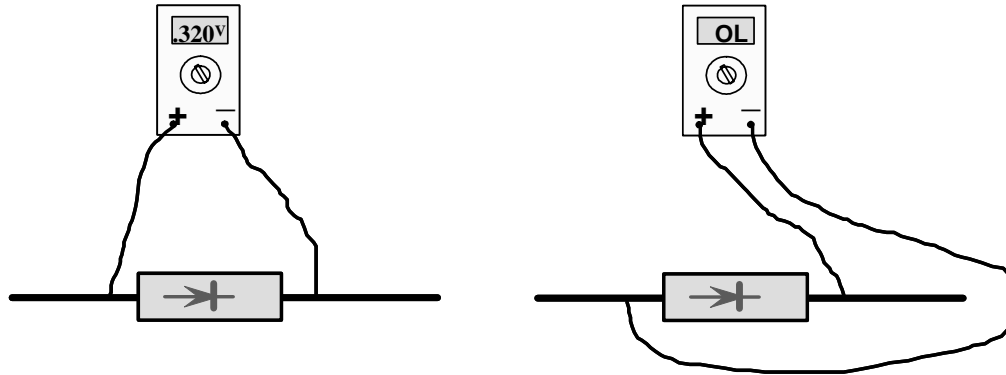
Testing Diodes

To check the diode bias, use the multimeter operated in the diode check mode (Figure 4.26). A functional diode will typically display a voltage from 0.3 V to 0.9 V in the forward bias; positive lead to anode, negative lead to cathode. In

the reverse bias condition, positive lead to cathode and negative lead to anode, a functional diode will display “OL” (overload or out of limits).

For shorted diodes, the meter will display some low voltage value in both forward and reverse bias configuration. In the case of an open-circuit diode, the meter will display “OL” in both forward and reverse bias.

To correctly verify diode operation, at least one lead must be disconnected from the circuit. Diodes cannot be properly checked while in the circuit or with the power on.



Check diode with power off and at least one lead disconnected from the circuit. Test in forward and reverse bias.

Figure 4.26 Diode Check

Diodes can be tested in a rectifier after it is turned off (locked out) after disconnecting the secondary taps and the DC cables. Each tap and each DC output terminal then represents a connection to a diode. Check the manufacturer's schematic diagram to confirm how the connections are made. Proceed with the diode test described in Figure 4.26. If an open circuit is indicated, check the connection wires and fuses in the circuit also. Connect the diode tester at (A), (B), (C) and (D) as shown in Figure 4.27.

D = Diode Tester

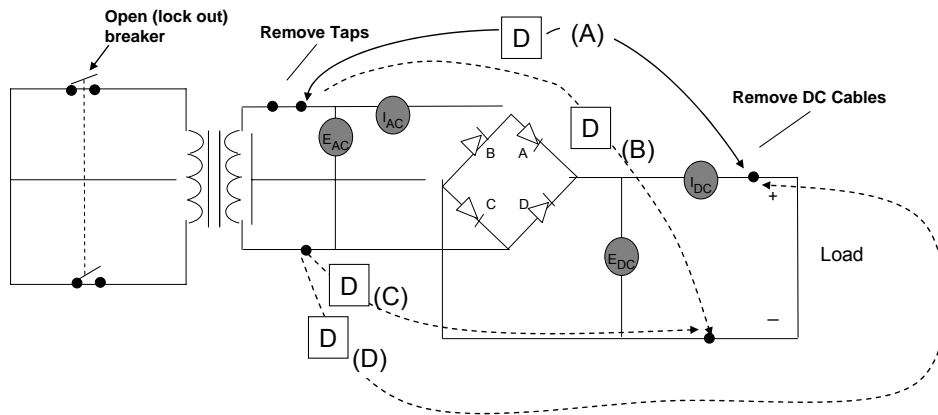


Figure 4.27 Single-phase Bridge Rectifier Circuit Showing Diode Test

Introduction

“Safety” is for your protection and that of your fellow worker. Although your company may take every precaution to keep you safe, your observations and actions on location will be the final determination as to whether you or someone else may be injured or killed. Safety may take some extra time but it cannot be compromised and must always be uppermost in your mind as you go about your work. No worker is required to work in unsafe conditions.

Some typical hazards that are encountered in cathodic protection testing or inspection are listed below. After a specific hazard assessment is completed for a particular job, the appropriate preventative measures must be determined to reduce higher risk and hazard exposure. This can be addressed by completing a Job Safety Analysis (JSA) that identifies each hazard and the preventative measures for each step of the project. The preventative measures are then incorporated into the job work procedure.

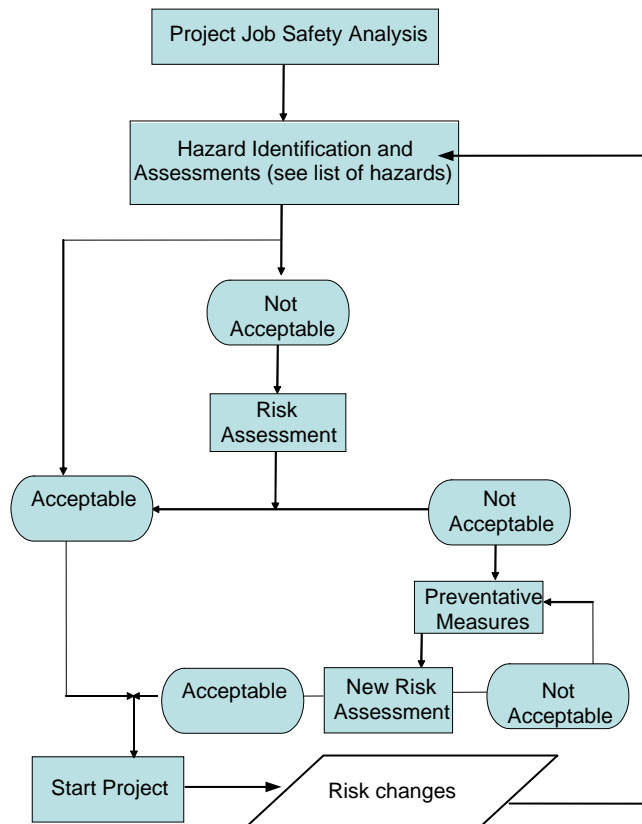


Figure 5.1 Safety Analysis Prior to Commencing Project

Some hazards that need to be considered include:

- Travel
 - Automobile or truck (highway or secondary roads)
 - All terrain vehicles (ATV)
 - Airplane
 - Helicopter
 - Boat
- Electrical
 - Rectifiers
 - Hazardous AC voltage on structures
- Environment
 - Atmospheric such as acid gases, H₂S
 - Soil and water pollutants
- Hazardous Materials
 - MSDS
- Trenches
 - Sloped or shored
- Reptiles, animals or insects
- Working at heights
 - Over land
 - Over water
- Working underwater
- Specific hazard(s) related to a project
- Confined space

This is not intended to cover a complete safety program. The following safety hazards are those specifically related to cathodic protection and are not always in a standard safety program.

Electrical

Cathodic protection testers and technicians can become complacent with electricity as in many cases the voltage being measured is very low with a low source of energy. This is not the case when working on electrical equipment such as rectifiers and associated electrical equipment or structures in the vicinity of AC power lines.

Electrical Equipment (Rectifiers)

Electrical Equipment (Rectifier) Case

Always assume that the electrical equipment or rectifier case may be poorly grounded and is inadvertently energized. This has happened! Before touching the case, either measure a case-to-ground voltage or use an instrument that detects AC voltage by a light that comes on when placed in close proximity. Do not touch the rectifier case while testing or in the first test do not extend your arms to bridge between the case and the ground probe. The case-to-ground voltage should be virtually 0 V_{AC}.

Remember it is the current through your body that kills. The values of current vary between the person and the length of exposure. The threshold of perception is generally agreed to be 1 mA. A current of 9 to 25 mA can cause lack of muscular control (let-go current) that makes it impossible to release and in fact it may cause the muscles to tighten.¹ Research indicates the maximum safe current between an arm and a leg is 100 mA at 3 seconds.² At a greater current, death may occur due to ventricular fibrillation of the heart.

Example:

If a person's resistance is 1000 Ω and contact is made with 120 V_{AC} then, using Ohm's Law ($I=E/R$), the current through the body is 120 mA, likely enough to be fatal. Note that rectifiers may be serviced with 240 V_{AC}, 480 V_{AC}, or up to 600 V_{AC} thus the body current would increase proportionally.

Cathodic Protection (CP) Rectifiers

- CP rectifiers have exposed electrical AC and DC terminals on the panel of the rectifier. The voltage exposure varies with the rectifier rating and design. Do not make body contact with any electrical terminal when the rectifier is energized and protect yourself from this hazard.
- Take measurements with insulated meter probes intended for that purpose using a one-hand method while avoiding contact to the probe end. Never press a probe end and a terminal or wire between your fingers to make a contact.
- Turning off the circuit breaker in the rectifier will render the front of the panel safe but will not make the back or inside of the rectifier safe!

¹ IEEE Std. 80, IEEE Guide for Safety in Substation Grounding, Institute of Electrical and Electronics Engineers

² L.P. Ferris, B.G. King, P.W. Spence, H.B. Williams, Effect of Electric Shock on the Heart, AIEE Trans., Vol. 55, pages 468-515 & 1263 May 1936 and IEEE Std 80.

- The AC disconnect outside the rectifier must be OFF (locked out/tagged out) before the entire rectifier is safe to work on.
- Confirm that the AC power is off by testing as breaker contacts can fuse together thus making contact in the tripped position.
- Lock out and tag the rectifier breaker or AC disconnect after turning OFF when installing an interrupter, changing taps, replacing components, or installing and removing the rectifier. This is a good habit to form and is required by code in many areas.
- There is no testing that is required behind the panel with the rectifier energized with the exception of measuring the input AC supply voltage. This AC voltage measurement is only to be completed by persons properly trained and is only to be measured if the terminals are readily accessible at the side of the rectifier. Remember that even with the rectifier breaker OFF, AC line voltage still exists up to the rectifier circuit breaker.
- Remember to turn OFF, lock out and tag the AC disconnect when working on or removing rectifier components. No one else can then inadvertently turn the AC on before it is safe.

Lock Out / Tag Out

A lock out / tag out (LOTO) is intended to ensure that the power can not be turned on inadvertently while people are still working on the equipment. In addition it instills a safe work habit. As an example seat belts in vehicles were felt a nuisance at first but now one feels uneasy if it is not on when the vehicle is in motion. The same applies to a LOTO where if it becomes a habit to follow this procedure, you will feel uneasy if it is not in place making you more aware of the hazard.

In many jurisdictions it is required by regulation. There are some common rules that apply:

- The person that installs the LOTO must be the one to take it off
- If there is more than one person working on the equipment, then a group scissor-type lock is to be installed with each person's lock on it (Figure 5.1).
- The tag identifies the person, contact information, date and the equipment being locked out.
- The equipment is not to be re-energized until it has been inspected to make certain it is safe and all locks have been removed by the owner of the lock.

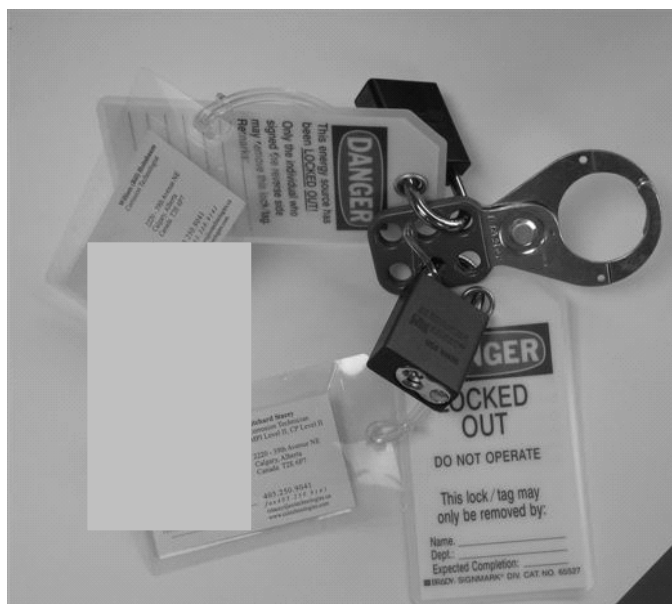


Figure 5.1 Group Scissor Lock Out / Tag Out (LOTO)

All cathodic protection personnel should carry a LOTO kit with them when in the field if they plan to work on rectifiers.

Electrical Hazardous Areas

Where there is a possibility of an explosive mixture of a hydrocarbon, the affected area will be designated as “hazardous” and electrical equipment must be contained in a sealed hazardous junction box. The CP technician must determine if he/she is qualified to work on electrical equipment in a hazardous area. Before electrical equipment is exposed in a hazardous area it must be turned off, locked out and tagged out to avoid the exposure of an arc that may act as a source of ignition.

Explosions or Ignitions

In addition to hazardous areas, many structures containing potentially explosive or combustible substances are cathodically protected. Under certain circumstances a cathodic protection system may have sufficient energy to ignite a combustible material or cause an explosion.

Whenever a current-carrying conductor is separated, depending upon the characteristics of the circuit, a spark may be generated. For example, a high-energy spark can occur on a cathodically protected pipeline carrying current back to the rectifier if the pipeline is cut or separated at a fitting. If a

combustible atmosphere is present, an explosion can occur. To avoid this situation, an electrical bond must be temporarily installed around the location where a pipe section is to be cut or a flange is to be disconnected.

Another situation where a high-energy spark may be generated is when a cathodically protected structure is inadvertently or purposefully electrically connected to another metallic structure. At the moment the connection is made, a spark may occur. For example when a ship or barge containing a combustible material docks at a cathodically protected dock, the barge and the dock will usually make electrical contact through metallic hawsers or other components. To avoid a potentially disastrous situation, standard practice involves bonding the dock and the barge using two bonding wires prior to opening any hatch on the barge. Using this technique, if a spark occurs, it occurs at the location where the bond is attached and prior to release of any potentially explosive vapors. Another precaution is to turn off the cathodic protection rectifier(s) until the vessel is securely bonded to the dock.

Finally, any cathodic protection component that might generate an ignition spark should not be allowed within specific areas where explosive atmospheres may exist. Examples are within dikes around tanks containing combustible materials, facilities housing or encompassing propane, natural gas or combustible product pipeline components, gas or oil production platforms, etc.

Standard rectifiers and many types of lightning arresters are potential ignition sources. In special situations where a rectifier must be installed in an area where explosive atmospheres could exist, an oil-immersed rectifier with explosion-proof fittings, switches, and components must be employed. Care should be exercised to ensure that the explosion-proof design of the equipment meets the classification of the area and that the design is not defeated by improper installation.

Cathodic Protection Surveys

There is always a possibility of encountering hazardous potentials while conducting cathodic protection measurements. A number of precautions are suggested:

- Assume that the potential to be measured may be hazardous. Do not contact a measurement circuit until the potential is determined to be safe.
- If AC may be present, measure AC voltage first.

- Avoid measurements during thunderstorms since hazardous voltages may occur on structures as a result of even remote lightning strikes.
- Use caution when working near power transmission lines or, when measuring across isolating devices and polarization cells, use one-hand connection method with insulated test leads and clips.
- Consider the possible shock hazards from operating CP systems in water.

Induced AC Voltages

In cases where a structure or tracer wires parallel a high voltage AC (HVAC) power transmission circuit, significant AC potentials may be encountered. Hazardous AC potentials can occur on a structure as a result of induction, ground return currents, or faulted power circuits.

The AC voltage-to-ground of a structure should always be measured first if there is a possibility of hazardous potentials. Be careful not to make direct physical contact with the measurement circuit. Use a multimeter to measure AC potentials between the structure and a copper-copper sulfate reference electrode in contact with the earth or other low resistance ground. If an AC voltage in excess of 15 V is measured, the structure is considered hazardous; and steps must be undertaken to reduce the hazardous voltage level. If the potentials are determined to be less than 15 V_{ac}, no specific action is necessary; however, caution should be maintained as this voltage can change at any time with a change in power line load.

NACE Standard RP0177, *Mitigation of Alternating Current and Lightning Effects on Metallic Structures and Corrosion Control Systems*, contains valuable AC safety information. You should become thoroughly familiar with this document especially Section 5, “Personnel Protection.” NACE Standard RP0177 is included in the Appendices section of the course manual.

A pipeline paralleling an HVAC transmission line can reach dangerous AC voltages when it is welded together on skids, but not backfilled. Special safety precautions must be taken when working around such lines. The safety precautions may include temporary electrical grounding of the pipe, avoiding physical contact with the pipe and other grounded structures and avoiding physical contact across electrically isolating joints. Safety precautions are given in the NACE International slide show entitled “Some Safety Considerations During Construction Near Power Lines.”

Always measure the AC voltage-to-ground voltage first before the DC structure-to-electrolyte potential or before touching the structure when in the vicinity of a power line.

Excavations

CP personnel are often need to enter excavations. There are regulations on the back sloping requirements for different soil conditions in every jurisdiction otherwise shoring is required. A ready means of exiting the excavation must be in place (ladders). Backfill and materials must be kept back a meter or more from the edge of the excavation if not secured. Water is to be kept from entering the excavation.

A safety person is to be on the surface while the worker is in the excavation and must remain there until the work comes out. No worker is required to work in conditions unsafe and can refuse to enter. Be aware that a person need not be completely buried to suffocate or have the heart receive a fatal shock.

Hazardous Material

During your work, you may encounter hazardous materials such as those listed below. Do not handle these materials unless you have the proper training or certification. These materials include the following:

- Solvents
- Acids used for cleaning metals
- Caustics used in polarization cells
- Chemicals used in reference electrodes.

Material Safety Data Sheets (MSDS)

Material safety data sheets (MSDS) are available for every chemical and many pieces of equipment. These sheets provide information about the hazards associated with chemicals, dust, corrosion products, etc., and provides valuable information for first aid or medical personnel. Among products for which safety information is available are:

- Copper sulfate

- Impressed current and galvanic anodes
- Metallurgical and petroleum carbon backfill.

MSDS sheets must be available for review.

- As required by law, always have MSDS sheets readily available for any chemicals that may be used.
- Know, understand, and follow the information and procedures given.

Reaction Products

In an operating cathodic protection system a number of gases may be generated either at the anode surface or at the cathode surface. Among possible gases that may be encountered are oxygen, chlorine, carbon dioxide, carbon monoxide, and hydrogen. Some gases are potentially explosive. Asphyxiation can occur due to the displacement of oxygen by some of the other gases listed. Some gases are toxic when inhaled. Low pH (acid) environments can exist around anodes in deep groundbeds.

Due to the potential problems mentioned, caution should be exercised to avoid situations where gases generated by a cathodic protection system might be allowed to collect.

Other General Precautions

Other precautions not discussed above that must be considered include:

- Wear protective eyewear, gloves, shoes and other clothing.
- Avoid open flames.
- Avoid causing electric sparks especially in areas that may contain a hydrocarbon.
- Know the handling/storage procedures for chemicals or other hazardous materials or equipment.
- Working at heights.

- Animals, reptiles and insects
- Vehicles: Drive defensively and be aware of hazard situations that could occur.

CHAPTER 6

Field Measurements

General

Knowledge of proper test procedures is an essential skill for a cathodic protection technician. You must be able to perform tests as they may be required and also be able to teach the procedures to entry level personnel. There is an expectation that students taking this course should have a number of years of field experience performing these tests and conducting surveys. They must know the instrumentation, understand the theory behind the tests, and be familiar with sources of error that can lead to misinterpretation of results.

Measurement of Cathodic Protection Effectiveness

Various techniques may be used to determine the degree to which a structure under cathodic protection (CP) is actually protected against corrosion, including:

- Structure-to-reference potential
- Test coupons
- Current measurements
- Surface potential measurements
- Soil resistivity
- Direct observation
- Leak frequency
- In-line inspection.

Structure-to-Electrolyte Potentials

The definition of a structure-to-electrolyte potential, otherwise referred to as a pipe-to-electrolyte, pipe-to-soil, tank-to-electrolyte, or structure-to-soil potential is:

“The potential difference between the metallic surface of the structure and electrolyte that is measured with reference to an electrode in contact with the electrolyte.”

A structure-to-electrolyte potential is a measurement taken with the voltmeter connected in parallel in the circuit. The external circuit resistance of this measurement is high, so a high-input resistance voltmeter is required to avoid “shunting” too much current from the structure and therefore achieving inaccurate measurements. In addition, as previously discussed a reference electrode, often referred to as a reference cell, is used to make contact with the soil.

Structure-to-electrolyte potential profile surveys are used to:

- Locate anodic areas on non-cathodically protected pipelines
- Determine the effectiveness of cathodic protection on cathodically protected structures
- Locate stray currents
- Locate electrical shorts and contacts
- Locate coating holidays.

Potential measurements are a common means for determining if adequate protection has been achieved. With the application of current from the environment onto a structure a potential change with respect to the environment will occur. The potential change is a reflection of polarization. Measurements are made to determine whether one of the cathodic protection criteria is met (see Chapter 2 for discussion on CP criteria). According to the NACE standards, voltage drops other than across the structure-to-electrolyte boundary must be considered in order to assess the effectiveness of a CP system using fixed potential measurements. Several methods are used to consider these voltage drops:

- Minimizing the distance between the reference electrode and the surface of the structure

- Measuring the potential when the current flow is interrupted (instant-off potential)
- Measuring the formation of polarization or decay of polarization of the structure when the current is energized or disconnected
- Installing external CP coupons in the vicinity of the structure to replicate a coating holiday

Advantages of the structure-to-reference potential method are that it is relatively straightforward and potential measurements comply with standard criteria. Disadvantages are that all sources of CP current must be interrupted simultaneously, stray currents will affect the readings, polarized potentials of structures with direct-coupled galvanic anodes cannot be obtained, and surface potential measurements actually measure average potentials. The averaging of the actual structure-to-electrolyte potentials means that surface measurements might not detect small corrosion cells that are not being cathodically protected.

The Potential Measurement Circuit and Measurement Error

The intent of the potential measurement is to determine the pipe potential (E_p) accurately at the test location. The measurement circuit can be approximated by the electrical circuit in Figure 6.1.

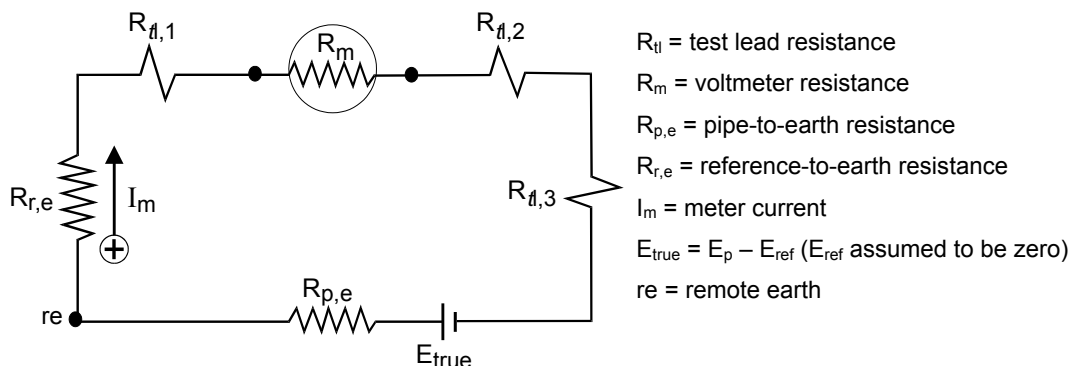


Figure 6.1 Electrical Schematic of the Structure-to-Electrolyte Measurement Circuit

It is the true potential difference (E_{true}) between the pipe and reference electrode that ideally should appear across the meter terminals. Because the meter circuit is a series circuit, the magnitude of the voltage drop that appears across the meter will be proportional to the ratio of the meter resistance to the total meter circuit resistance.

For the measurement circuit, Kirchhoff's voltage law applies and the true potential difference is equal to the sum of the voltage drops around the series circuit.

$$E_{true} = I_m R_t \quad \text{Eq. 6-1}$$

$$E_{true} = I_m [R_{tl,1} + R_{tl,2} + R_{tl,3} + R_{p,e} + R_{r,e} + R_m]$$

$$E_{true} = V_{tl,1} + V_{tl,2} + V_{tl,3} + V_{p,e} + V_{r,e} + V_m$$

$$V_m = E_{true} - [V_{tl,1} + V_{tl,2} + V_{tl,3} + V_{p,e} + V_{r,e}]$$

Let V_{circ} equal all voltage drops in the circuit except for the meter voltage drop

$$V_m = E_{true} - V_{circ}$$

$$\text{but: } E_{true} = I_m R_t \text{ and } V_{circ} = I_m R_{circ}$$

$$\text{and: } R_t - R_{circ} = R_m$$

$$\text{then: } \frac{V_m}{E_{true}} = \frac{R_m}{R_t} \quad \text{Eq. 6-2}$$

Hence, the amount of voltage (V_m) that appears across the meter compared to the true potential difference (E_{true}) is proportional to the ratio of the meter resistance (R_m) compared to the total resistance.

For example: Consider a true potential (E_{true}) of 1,000 mV, each test lead resistance (R_{tl}) of 0.01 Ω , a pipe-to-earth resistance ($R_{p,e}$) of 10 Ω , a reference electrode resistance to earth ($R_{r,e}$) of 100 k Ω , and a meter resistance (R_m) of 1 M Ω . Calculate the voltage that would appear across the voltmeter.

$$\begin{aligned} R_t &= 3R_{tl} + R_{p,e} + R_{r,e} + R_m \\ &= 3(0.01) + 10 + 10^5 + 10^6 \\ R_t &= 1.1 \text{ M}\Omega \end{aligned}$$

From Equation 6-2

$$V_m = \frac{R_m}{R_t} \times E_t$$

$$V_m = \frac{1.0 \text{ M}\Omega}{1.1 \text{ M}\Omega} \times 1,000 \text{ mV} = 909 \text{ mV}$$

This is an error of:

$$\frac{1,000 - 909}{1,000} \times 100 = 9\%$$

If the meter input resistance in the foregoing example is increased to 10 MΩ, the voltmeter would read 990 mV which would reduce the error to 1%.

The voltage across the voltmeter approaches the true potential as the meter resistance becomes much greater than the other resistances in the measuring circuit.

High resistances in the measuring circuit, other than across the voltmeter, should therefore be avoided. Reference electrode contact resistance can be a source of error when the reference is placed on dry soil, well drained gravel, crushed stone, frozen ground, asphalt, or concrete. To minimize this error, the contact conductance can be improved by wetting the area around the reference. In extreme cases, a hole can be drilled from the surface to a depth of permanent moisture and the reference placed in the hole, or an electrolytic bridge can be created between the reference and earth (Figures 6.2a and 6.2b).

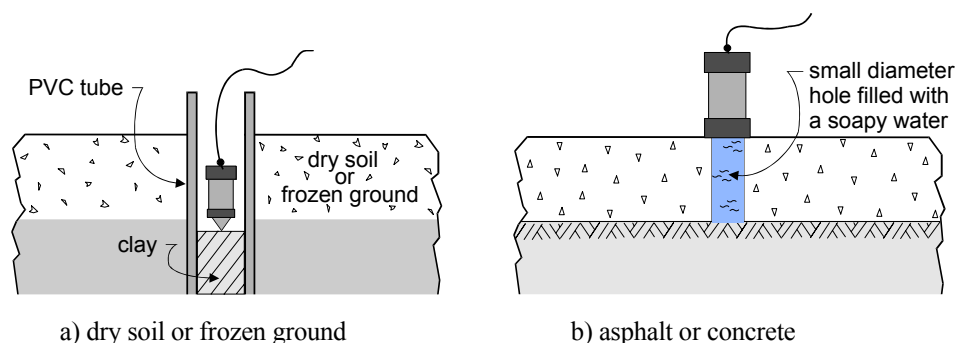


Figure 6.2 Methods of Minimizing Reference Electrode Contact Resistance

In Figure 6.2a, the depth from grade to clay must be below the frost line in frozen soil and to the depth of permanent moisture in dry soil. For asphalt or concrete, a soapy water solution will usually provide sufficient electrolytic contact even if the water level in the hole drops.

High measurement circuit resistance can also occur as a result of broken test leads, test lead connection resistances, and pipe resistance to earth if the pipeline is short and well coated.

When measuring a pipe-to-soil potential, it may not be immediately apparent that a high circuit resistance is present. If the voltmeter has an input resistance selector switch the existence of a high resistance in the measurement circuit can be identified by switching to a lower or higher input resistance. If the potential indicated by the voltmeter differs significantly (i.e., more than 10%) between the two input impedances then there is a high resistance in the measurement circuit. Further by knowing the two input resistances and their corresponding measured voltage, the true potential can be calculated using Equation 6-3.

$$E_{\text{true}} = \frac{V_h (1 - K)}{1 - K \frac{V_h}{V_l}} \quad \text{Eq. 6-3}$$

where:

- E_{true} = true potential (V)
- K = input resistance ratio R_l/R_h
- R_l = lowest input resistance
- R_h = highest input resistance
- V_l = voltage measured with lowest input resistance
- V_h = voltage measured with highest input resistance

For example: If a potential difference (V_l) of $-650 \text{ mV}_{\text{cse}}$ was measured with an input resistance (R_l) of $1.0 \text{ M}\Omega$ and a potential difference of $-800 \text{ mV}_{\text{cse}}$ (V_h) was measured with an input resistance (R_h) of $10 \text{ M}\Omega$, then the true potential (E_{true}) would be calculated as follows:

$$\begin{aligned}
 E_{\text{true}} &= \frac{-800 \text{ mV} (1 - 0.1)}{1 - 0.1 \left(\frac{-800 \text{ mV}}{-650 \text{ mV}} \right)} \\
 &= \frac{-720 \text{ mV}}{1 - 0.123} = \frac{-720 \text{ mV}}{0.877} = -821 \text{ mV}_{\text{cse}}
 \end{aligned}$$

E_{true} is the same as the polarized potential.

In addition, the total circuit resistance (R_t) can be determined using Equation 6-2.

$$\begin{aligned}
 R_t &= \frac{R_m \times E_{\text{true}}}{V_m} \\
 &= \frac{10 \text{ M}\Omega \times 821 \text{ mV}}{800 \text{ mV}} \\
 R_t &= 10.3 \text{ M}\Omega
 \end{aligned}$$

This means that the resistance in the measuring circuit, excluding the meter resistance is:

$$\begin{aligned}
 R_{\text{circ}} &= R_t - R_m \\
 &= 10.3 \text{ M}\Omega - 10 \text{ M}\Omega \\
 R_{\text{circ}} &= 0.3 \text{ M}\Omega \text{ or } 300,000 \Omega
 \end{aligned}$$

As charges flow in the earth to or from the pipe and with earth's resistance, voltage drops occur in the earth creating a voltage gradient around the pipe as illustrated for a bare pipe in Figure 6.3.

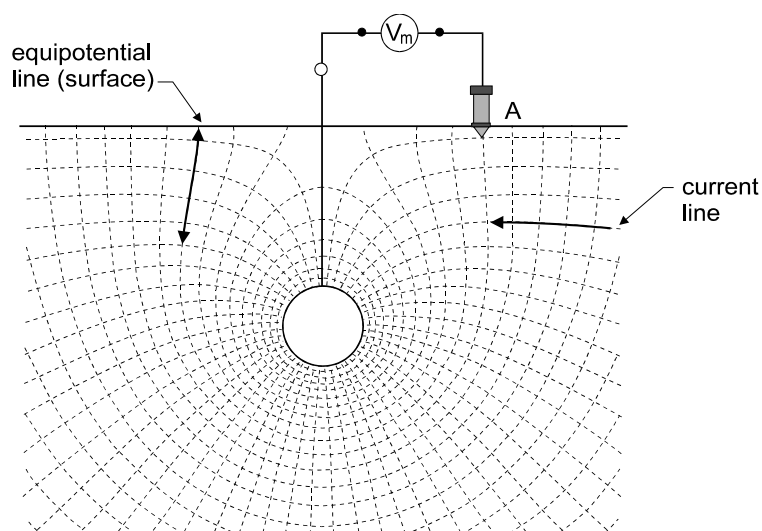


Figure 6.3 Voltage and Current Lines around a Bare Pipeline Receiving Cathodic Protection Current

Source: Parker, Marshall and Peattie, Edward, Pipeline Corrosion and Cathodic Protection, 3rd Edition, Gulf Publishing Co., Houston, TX, p.25

The radial lines denote the current paths while the lines perpendicular to the current lines represent the equipotential surfaces created by the current. The equipotential surfaces, which are perpendicular to the current paths, are not evenly spaced but increase with distance away from the pipe because each successive shell of earth has a larger surface area and hence a lower resistance.

If a potential measurement is taken with the reference electrode located at A and the current direction is toward the pipe (as would be the case in cathodic protection), then there is a voltage drop (V_s) in the soil between the reference electrode and the pipe surface. The soil at point A is more positive than the soil immediately adjacent to the pipe surface. If the potential difference between adjacent equipotential surfaces is 10 mV, the voltage drop in the soil between the pipe surface and the reference location would be 10 lines \times 10 mV = 100 mV. The soil at the pipe surface is -100 mV with respect to the soil at the reference electrode.

For example, if the polarized potential (E_p) of the pipe is $-790 \text{ mV}_{\text{cse}}$ the voltmeter will read:

$$V_m = -790 \text{ mV}_{\text{cse}} + (-100 \text{ mV})$$

$$V_m = -890 \text{ mV}_{\text{cse}}$$

Thus, there is a 100 mV error in the measurement that makes it appear as if the pipe is better protected than it is.

For a well coated pipeline, the equipotential field forms in close proximity to the holidays as shown in Figures 6.4 and 6.5.

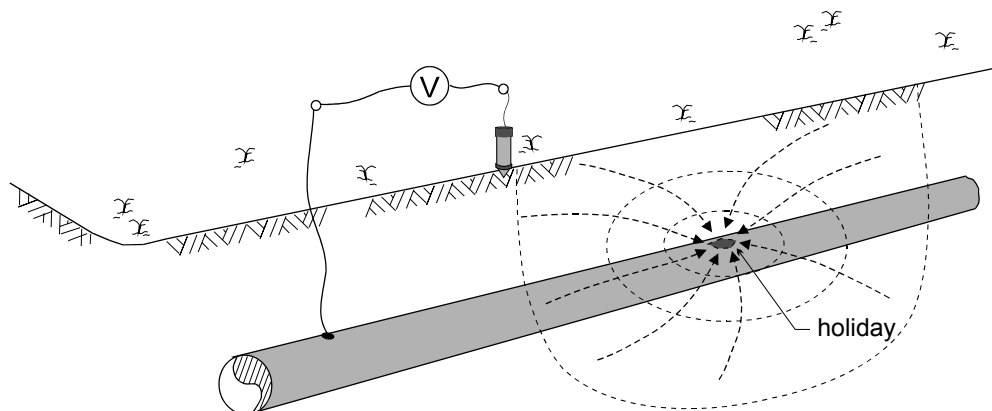


Figure 6.4 *Current and Voltage Lines around a Holiday on a Coated Pipeline*

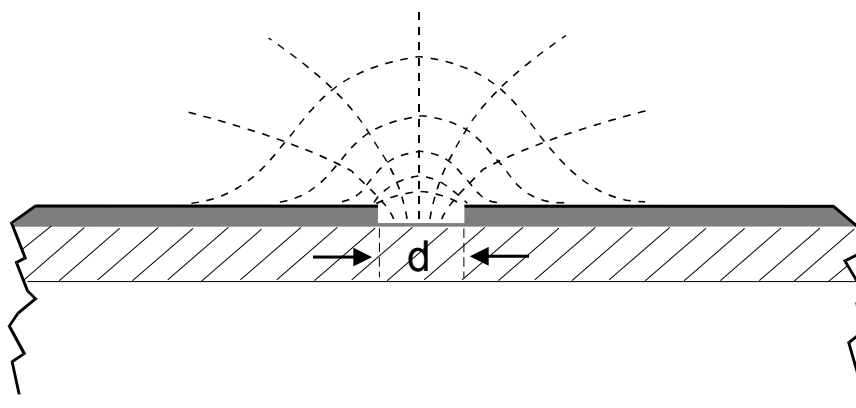


Figure 6.5 *Current and Voltage Lines in Immediate Vicinity of a Holiday*

On a coated pipeline, most of the voltage drop is concentrated in the immediate vicinity of the holiday. Typically 95% of the total voltage drop between the reference and the steel exposed at the holiday is found within about 10 diameters of the holiday (i.e., 10 d). For a 1 cm diameter holiday, 95% of the voltage occurs within a radius of 10 cm from the holiday.¹

¹ Gummow, R.A., The Cathodic Protection Potential Criterion for Underground Steel Structures, NACE International, CORROSION/93, Paper No. 564, p. 5.

Voltage Drop Errors in the Potential Measurement Due to Current in the Pipeline

Voltage drops also occur in current-carrying metal paths and if the connection to the pipe is remote from the location of the reference electrode, as shown in Figure 6.6, there will be an IR drop error (V_p) in the potential measurement.

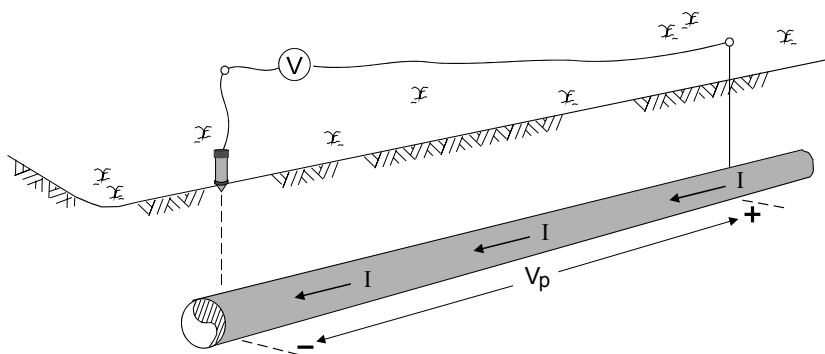


Figure 6.6 Voltage Drop in a Pipeline Carrying Current

IR Drop Error Determination and Correction

Potential measurements often include errors caused by IR drops, particularly in the electrolyte, as discussed previously. Furthermore, the magnitude of IR-drop errors must be determined and appropriately compensated for when measuring and evaluating field data. Accordingly, there are a number of common methods of determining and correcting for IR drop:

- Interrupt the current and measure the potential before significant depolarization occurs (often called the “instant off” potential).
- Place the reference electrode close to the exposed metal surface of the structure being measured. On a coated structure the reference must be placed next to a coating fault (holiday).
- Place the reference electrode at remote earth to include maximum IR-drop error and then subtract this error from potentials measured with the reference located nearer the structure.
- Decrease the current in steps while measuring the change in structure-to-electrolyte potential and the resultant surface voltage gradient. The curve created from this data is extrapolated to zero current to identify total IR-drop error in the structure-to-electrolyte potential at full current.

In some situations, the IR-drop error can be neglected if the current and/or the resistance of a current path that is a function of the path's cross-sectional area, resistivity, and length, is small. Before neglecting the IR drop, the magnitude of IR drop should be determined in order to verify its insignificance.

Current Interruption

An effective method of eliminating IR-drop errors is by making the current zero thereby making the IR product equal to zero. Typically, zero IR drop is achieved by temporarily interrupting the flow of current and instantly reading the structure potential. This potential must be read quickly since the structure will begin to depolarize with time (see Figure 6.7).

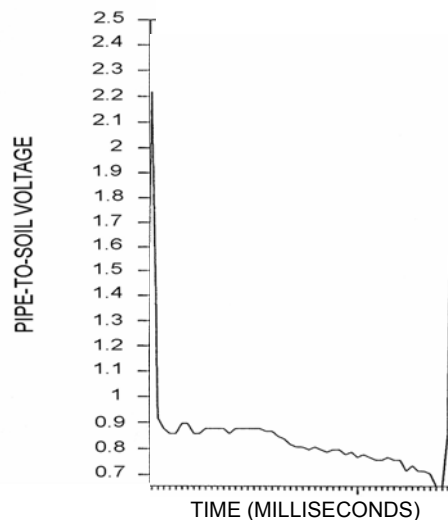


Figure 6.7 Waveprint Illustrating Depolarization During OFF Cycle

However, there may be significant spiking of the potential due to inductive and capacitive effects associated with the interruption of the cathodic protection current. The “instant-off” potential should be measured after this spiking has decayed (see Figure 6.8) but before significant depolarization of the structure has occurred.

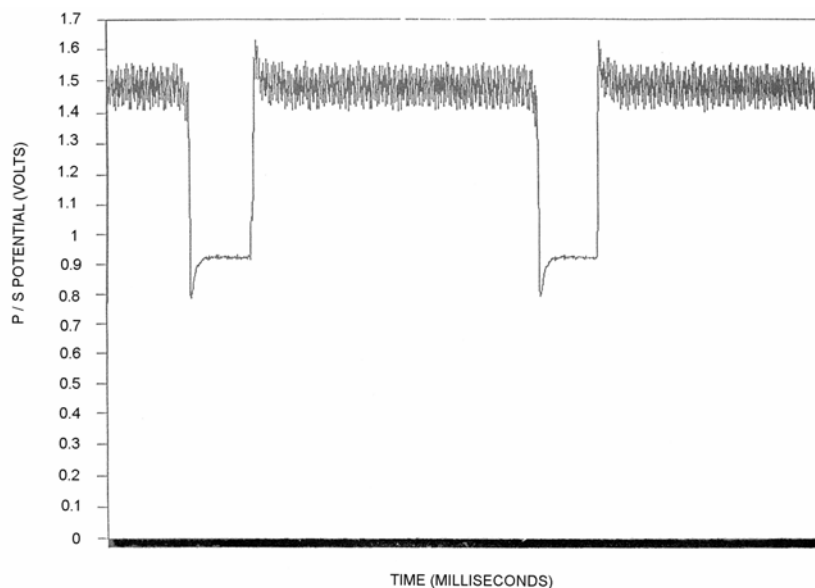


Figure 6.8 Structure-to-Electrolyte Potential “Waveprint” Illustrating the “Spike” During Current Interruption

To measure the “OFF” structure-to-electrolyte potential, all sources of current influencing the area under investigation must be interrupted. This can be accomplished by installing a current interrupter in all current sources influencing the system in the area under investigation. The interrupters are essentially a mechanical or electronic relay connected to a very precise chronometer. Multiple units can be synchronized to cycle in unison, allowing multiple current sources to be interrupted simultaneously, effectively removing all current from the structure at the same instant. With no current flowing, the voltage drops go to zero and the measured potential is the polarized potential of the pipeline.

$$\text{Potential Measured (E}_m\text{)} = E_{\text{corr}} + \text{Polarization} + \text{IR Drop} \quad \text{Eq. 6-4}$$

This is illustrated in Figure 6.9.

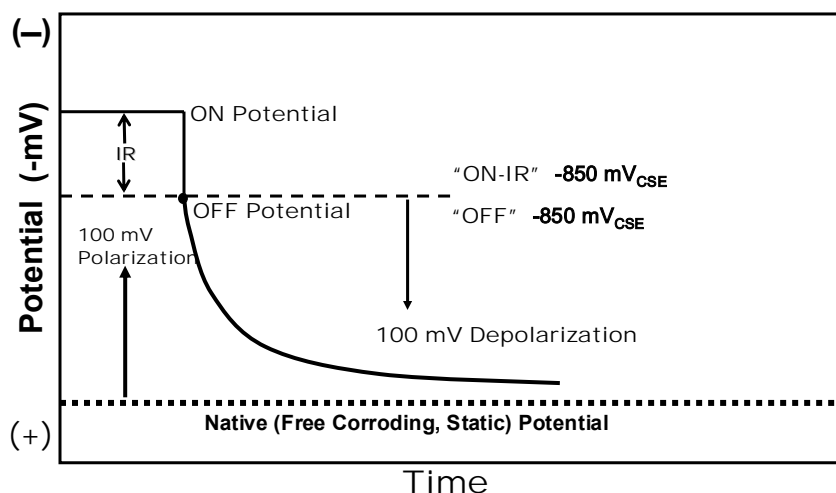


Figure 6.9 Elimination of IR Drop by Current Interruption and Subsequent Depolarization

This technique has the added advantage that the IR drop in the circuit's metallic path is also eliminated. On structures having multiple current sources influencing the potential reading it may be difficult to interrupt all the sources or to interrupt them simultaneously. Since IR drop at any given location is the sum of the effects of current applied at all sources, the total IR drop can be calculated by summing the individual effects.

Interruption cycles vary based upon the type of structure-to-electrolyte potential survey that is being conducted. Key factors in selecting an interruption cycle include:

- Minimizing depolarization during the day
- Minimizing depolarization during the OFF period
- Maintaining polarization over the duration of the survey project
- Ability to measure accurate OFF potential data after the "spike" has dissipated.

Maintaining an 80%/20% or 75%/25% "duty cycle" is important to minimize depolarization during the day and over the duration of the survey project. The duty cycle is the percentage of ON time to OFF time. An example would be 3 seconds ON and 1 second OFF.

In addition, it is important to turn off the current interrupters at night. This will reduce the amount of time the current sources are being cycled and help rebuild any polarization which may have been lost during the day when the current sources were cycling ON and OFF.

Maintaining the synchronization of the current interrupters is accomplished by several means. Current interrupters available today include quartz crystal timing devices which, once synchronized together, will maintain the timing for a period of time. The United States government's Global Positioning Satellites (GPS) system also provides precise timing and is available at no charge to the public. GPS-synchronized interrupters which maintain precise timing indefinitely as they "resynchronize" themselves at predetermined times throughout the day are available. Note that some will fail in the on position if they lose their satellite signal and then restart when it comes back. Unless there is a stationary datalogger monitoring the data, this event can go unnoticed and true polarized potentials will not be taken.

One method of verifying interruption synchronization and of checking the magnitude and duration of the inductive/capacitive spike is by recording a "wave print" or waveform. A wave print is a graph of hundreds or thousands of structure-to-electrolyte potentials recorded every second for the duration of an interruption cycle. The data is graphed versus time and can be reviewed in the field to review:

- Interrupter synchronization (see Figure 6.10)
- Depolarization during the OFF period (see Figure 6.7)
- Spiking magnitude and duration (see Figure 6.8)
- Dynamic stray currents (see Figure 6.11)

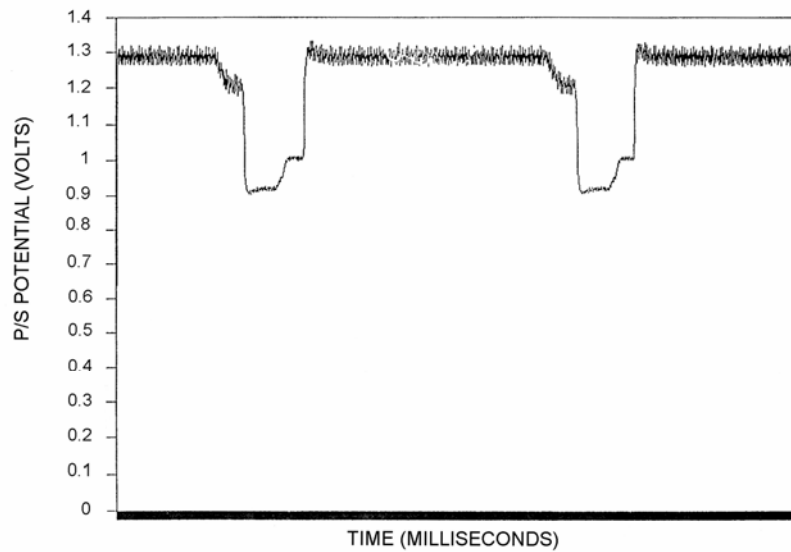


Figure 6.10 Waveprint Illustrating Non-Synchronized Current Interrupters

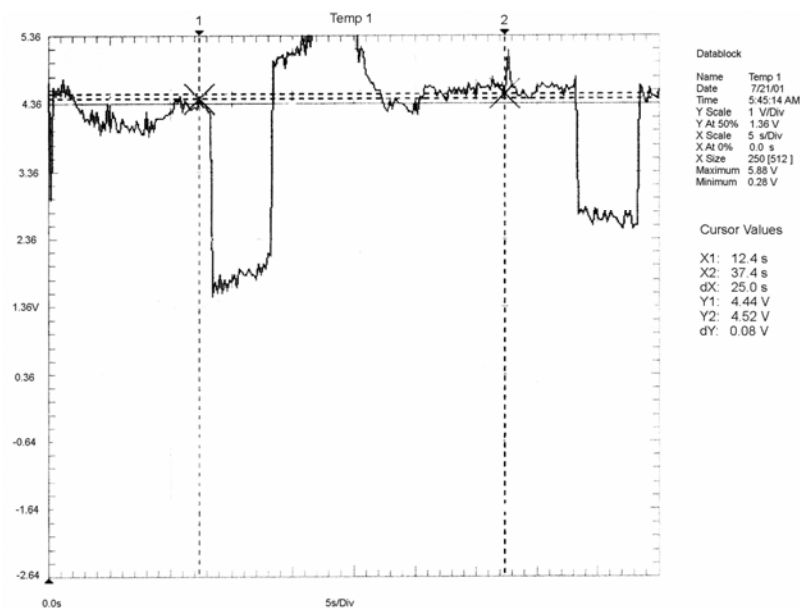


Figure 6.11 Waveprint Illustrating Dynamic Stray Current Interference

Reference Electrode Near the Structure

To minimize the IR-drop error associated with the electrolyte, the reference electrode should be positioned as near to the structure as possible. This may not eliminate all IR drop.

When dealing with underground piping or tanks, the ideal position of the electrode would be at the bare structure surface or at a coating holiday. There are times, however, when the electrode is purposely placed at some distance from the structure; this is discussed later under the section “Remote Earth.”

Inside water storage tanks, the electrode should be positioned as close to the wall of the tank as possible. The same is true for waterfront and offshore structures; the electrode should be as close to the piling as possible. In moving water, the electrode may swing about, so some structures are equipped with guide wires or perforated plastic ducts to restrict the movement of a portable electrode.

For on-grade storage tanks, data are frequently taken around the periphery of the tank. This may not yield accurate data about the potentials under the tank bottom, particularly if the anodes are in a ring around the tank or the tank is large in diameter. Stationary reference electrodes under the tank bottom yield the best data. Alternately, if a perforated plastic tube is installed under the tank and filled with water, a reference electrode can be pulled through it and potentials measured at intervals underneath (see Figure 6.12).

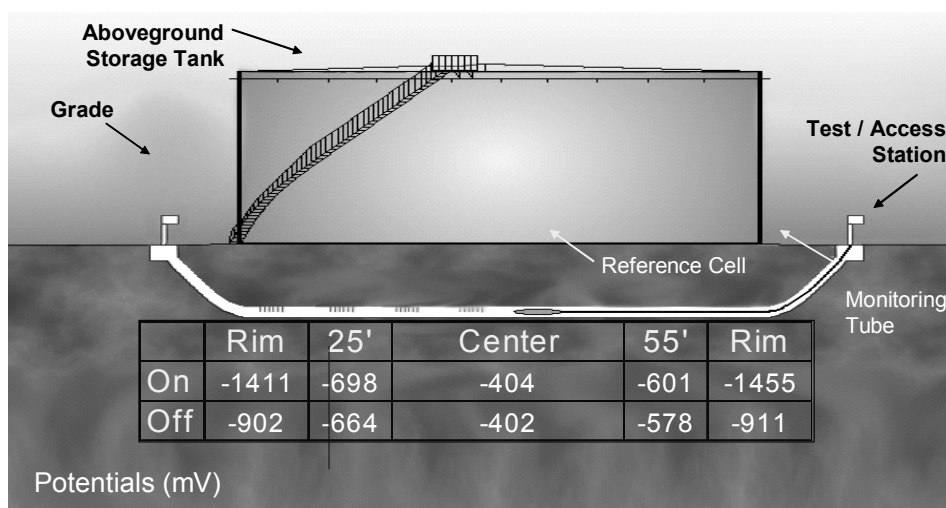


Figure 6.12 Reference Cell Under AST

Placing the reference electrode close to the structure minimizes the IR-drop error in the electrolyte in proportion to the electrode's closeness of the electrode to the surface. Unfortunately, for underground structures, this is not a practical technique except at points of structure-to-soil entry and exit. Also, on coated structures, the electrode cannot normally be placed any closer to the structure than a point immediately outside the coating, and it is across the coating where much of the IR drop exists (Figure 6.4).

External CP Coupons

Evidence that cathodic protection is working can be obtained by using coupons of the same metal as that of the protected structure. These coupons are weighed carefully beforehand, and then electrically connected to the protected structure. The coupons should be placed where they receive the same exposure to cathodic protection current as the structure receives; then, after a known exposure time, they are removed and weighed. Corrosion rate is the weight loss per time.

External CP coupons can also be used to monitor cathodic protection criteria. This is particularly useful on well-coated structures where few coating holidays exist. The coupon serves as a surrogate holiday and polarizes to the same structure potential (Figure 6.13).

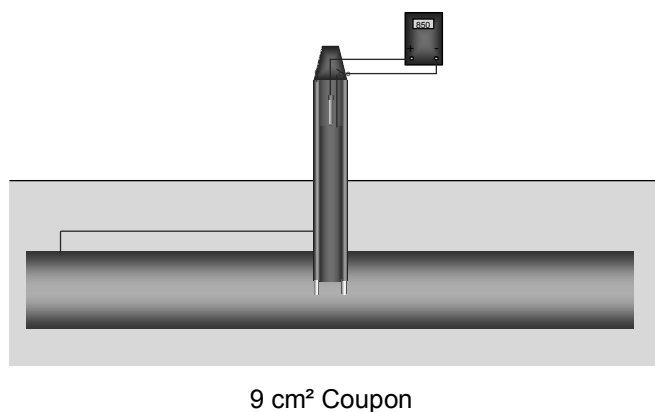


Figure 6.13 External CP Coupon

Advantages of using CP coupons are that IR-drop-free potentials can be obtained without interrupting multiple power sources, structure-to-reference potentials can be measured on structures with direct-connected galvanic anodes, and depolarization tests can be conducted on the structure without de-energizing the CP system.

It should be understood that there can be a discrepancy between the polarized potential of the coupon and that of the structure.

A number of special cathodic protection monitoring test stations are available. These are constructed with a steel coupon connected through the test station wiring to the structure that is under cathodic protection. The test station is positioned so that the coupon rests near the structure in the same backfill around

the structure. A reference electrode is placed in the test station riser, in the soil near the coupon, or at grade to permit measurement of the coupon to electrolyte potential. The coupon is momentarily disconnected from the structure and its potential with respect to the electrolyte is read.

This allows an essentially IR-drop-free reading of the coupon potential to the reference electrode and therefore the equivalent instant-off potential of the structure since they should both have been at the same potential before the reading is made.

Some of these test stations are available with resistance-type corrosion probes located in the foot of the test station. The element is connected to the structure and is under the same level of cathodic protection as the structure. If corrosion is occurring, the resistance probe will reflect the condition by showing a higher resistance over time. Figure 6.14 illustrates one type of special test station that includes the features described.

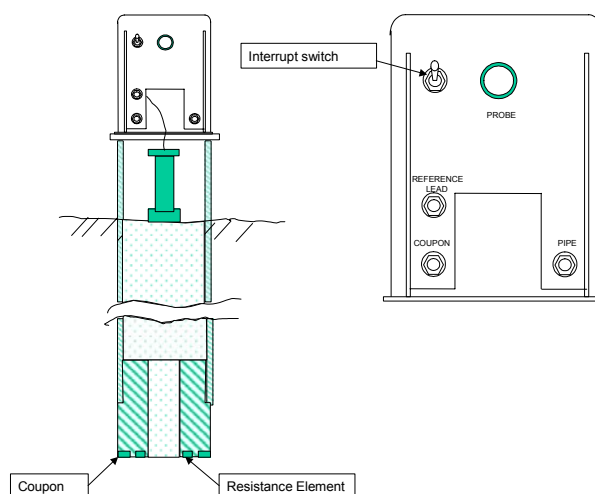


Figure 6.14 Special Test Station for Monitoring Cathodic Protection

Figure 6.15 shows a coupon test station designed to monitor cathodic protection levels on pipelines or other buried structures. Coupons can also be used for submerged structures (such as water tanks, clarifiers, dock structures, and offshore structures), in reinforced concrete structures, or in any other structure being cathodically protected.

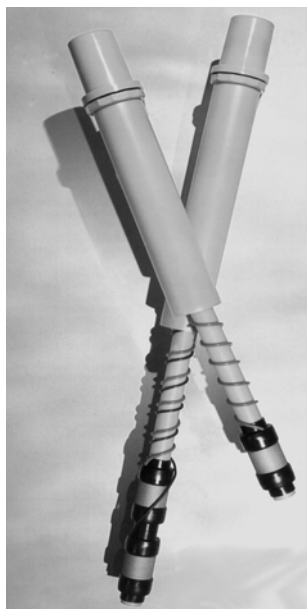


Figure 6.15 Two Types of Coupon Test Stations
(Courtesy of Cott Manufacturing Company)

Resistance probes are available that will monitor corrosion rate directly without being removed from the environment. As a metal corrodes, its volume is reduced, which causes its electrical resistance to increase. These probes work by sensing the increase in resistance of the probe (made of the metal being tested) as the metal corrodes. An instrument at a test station measures the resistance changes, which are then used to determine the corrosion rate. The corrosion rate of the probe on a cathodically protected structure will be zero. The probes can also be used for potential and polarization measurements.

Reference Electrode at Remote Earth

With the reference electrode remote from the structure, the potential reading includes the maximum total IR-drop error when the current is applied. Accordingly, by identifying the maximum value between a reference electrode placed at the pipe surface and a remote reference electrode, this value can be subtracted from subsequent structure-to-electrolyte potential readings as long as the current density and path resistivity remain relatively constant. When constant conditions are present, this technique would probably result in overcorrection of the potential reading, thus erring on the safe side.

Remote earth may be determined by a series of structure-to-electrolyte potential measurements made as one moves away from the structure. Typically, these measurements are made at consistent intervals and presented in graphical form. Figure 6.16 indicates that at points some distance from the structure, there is little increase in the magnitude of the potential. Beyond this distance may be considered electrically remote for practical purposes.

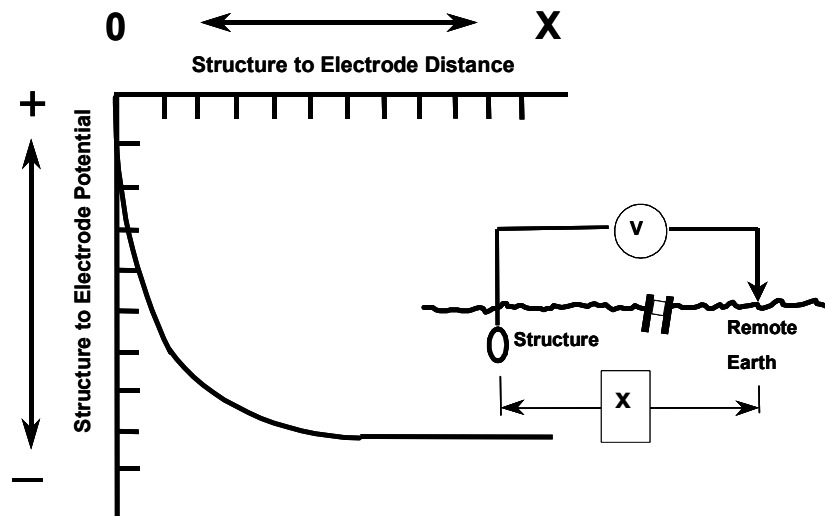


Figure 6.16 Determination of Remote Earth from Structure

The distance to remote earth is not necessarily the same at all points on a structure. Both soil resistivity and current density have an effect. In high-resistivity soil areas, the distance to remote earth tends to be greater than in low-resistivity soils.

Stepwise Current Reduction Method

The stepwise current reduction technique involves recording the potential shift in the structure-to-electrolyte potential measurement and a side drain potential measurement as the cathodic protection current is reduced. The test arrangement is illustrated in Figure 6.17.

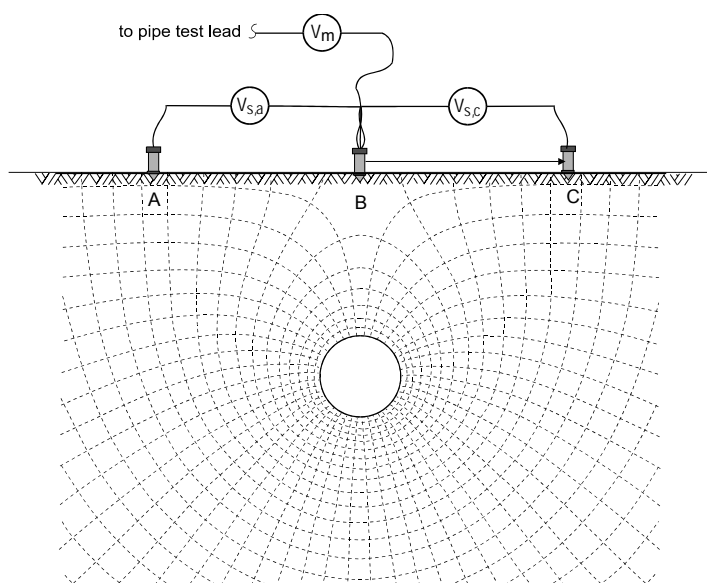


Figure 6.17 Field Test Arrangement for the Stepwise Current Reduction Method of Determining the Amount of IR drop in the On-Potential

The on-potential recorded on the voltmeter (V_m) is

$$V_m = E_p + I_{cp} \cdot R_e \quad \text{Eq. 6.5}$$

If the I_{cp} current was reduced the on-potential would decrease because the earth voltage drop ($I_{cp}R_e$) would decrease. If the stepwise reduction in cathodic protection current was continued until $I_{cp} = 0$, then $V_m = E_p$ and the IR drop would also be zero. Further, the side drain potentials $V_{s,c}$ and $V_{s,a}$ should also approach zero as I_{cp} approaches zero. Assuming the earth voltage drop $I_{cp}R_e$ and the side drain voltages obey Ohm's law, then these parameters should be linearly related.

By reducing the cathodic protection current in increments and measuring V_{on} , $V_{s,c}$, and $V_{s,a}$, the data can then be used to construct the graph of Figure 6.18.

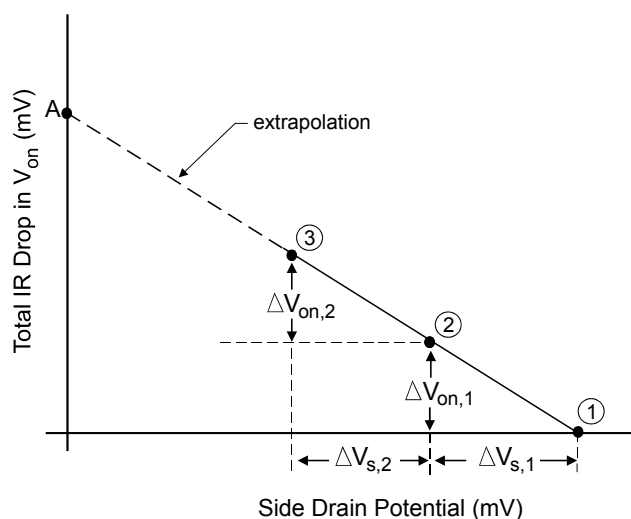


Figure 6.18 Data Plot for Stepwise Current Reduction Technique

- Step ① Plot $V_{s,a}$ or $V_{s,c}$ on the abscissa with full current
- Step ② Reduce I_{cp} , calculate ΔV_{s1} , and $\Delta V_{on,1}$;
plot ΔV_{s1} and $\Delta V_{on,1}$ to obtain point ②
- Step ③ Repeat Step ② and plot ΔV_{s2} and $\Delta V_{on,2}$ to obtain point ③
- Step ④ Draw a best fit straight line through the data points and extrapolate the line until it intersects the ordinate at A.

“A” on the “y” axis is then the amount of IR drop in the original on-potential measurement. The polarized potential (E_p) is then determined by subtracting the IR drop at A from the on-potential measured at location B i.e.,

$$E_p = V_{m,b} - A \quad \text{Eq. 6.5}$$

Two lines could be plotted for both side drain measurements that should give the same intercept A if the current and soil resistivity is symmetrical around the pipe.

Current reduction time intervals should be kept as short as possible, otherwise the polarized potential (E_p) will reduce as well as the earth IR drop and result in a larger IR drop indication. If the potential changes are recorded quickly, this technique can be used in the presence of dynamic stray currents.

The technique is time consuming and seldom used since if it is possible to reduce the cathodic protection current it is possible to interrupt the current and use the current interruption technique.

Theoretically, this method could be used on piping with attached galvanic anodes by applying a test current in increments. This would then be a stepwise current increase technique.

On very well coated pipelines, the side drain potential may be small which would increase the angle of the line such that a small error in plotting would result in a large change in the point of interception. Hence, its accuracy for well coated pipelines may be compromised.

Surface Potential Surveys

Surface potential surveys are used for many purposes and can be broken down into structure-to-electrolyte surveys, coating defect surveys, and earth current surveys.

A structure-to-electrolyte potential is the potential difference between the structure and a standard reference electrode. There are four elements that must be recorded including the value, the polarity, the units, and the reference electrode used.

Since this measurement is often used to determine if a criterion for cathodic protection is met, the readings must be IR-drop free and sufficient readings must be taken to be confident that a representative number of locations have been tested to provide an accurate picture of the status of protection throughout the structure.

Potentials are taken at intervals close enough to provide a clear understanding of the status of protection. Where potentials may vary quickly along a pipeline, a close interval potential survey (CIS) should be conducted.

Close Interval Potential Survey

A series of structure-to-electrolyte potentials determine if adequate cathodic protection is achieved at all points along the structure. Figure 6.19 illustrates a close interval potential profile.

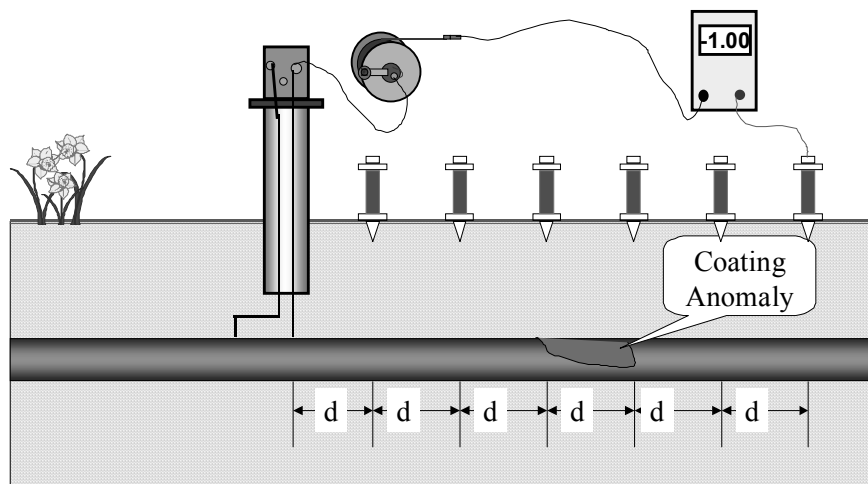


Figure 6.19 Close Interval Potential Survey

In a close interval survey (CIS), the structure-to-electrolyte potential data are collected at close spacing [1 to 5 m (3 to 15 ft)]. This is usually done by carrying a voltmeter or datalogger and a wire-dispensing device. Some wire dispensing devices are equipped with distance measuring capability so that the technician knows where they are when the data is entered into the data logger. Others simply use a measuring chain or calibrated rope and “station” the pipeline using the company’s pipeline as-built information.

A close interval potential survey can be completed on both cathodically protected and non-cathodically protected structures.

One or two reference electrodes, mounted at the end of a short pole(s), are used. A small-gauge wire, usually 30 to 34 AWG size, is attached to a test station or other abovegrade electrically continuous structure and the operator walks over the pipeline, making contact between the electrode(s) and the earth at closely spaced intervals. The operator records abovegrade appurtenances and other identifying items along the way so the location of the data can be pinpointed. During the survey, the data is downloaded into a computer and often printed in graph form (Figure 6.20).

If a single reference electrode is used the operator signals the datalogger to save the readings after a good reference contact is made. Where soil conditions are favorable a “walking electrode” procedure can be used where one reference electrode is in contact with the soil at all times and the datalogger saves the readings based on an odometer input determined from the wire passing through it.

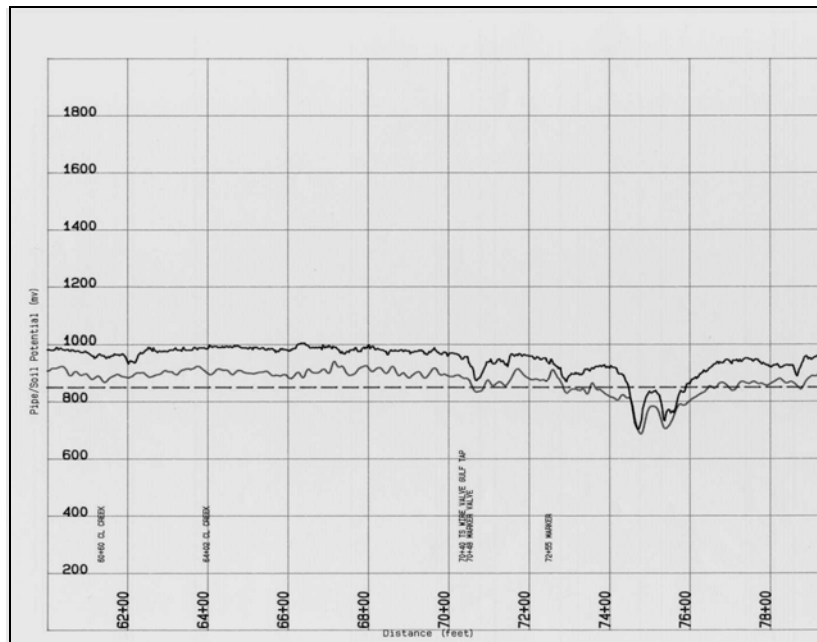


Figure 6.20 On/Off Pipe-to-Electrolyte Potential Profile

When testing multiple pipelines that are bonded together, the survey data will represent an average potential of all the pipelines.

If the target CP criteria is the $-0.850 V_{CSE}$ polarized potential criteria, then typically an interrupted CIS where the influencing current sources are interrupted and both ON and IR-drop-free (“instant-off”) potentials are completed. For the 100 mV polarization criteria, after the ON/OFF potential data has been collected, the current sources are de-energized and a period of time allowed for the structure to depolarize. Once depolarized, a second CIS is completed collecting depolarized pipe-to-electrolyte potentials at the exact reference electrode locations as during the initial CIS. This data can then be overlaid on the same graphs with the ON/OFF data to confirm whether or not the 100 mV criteria has been satisfied (Figure 6.21).

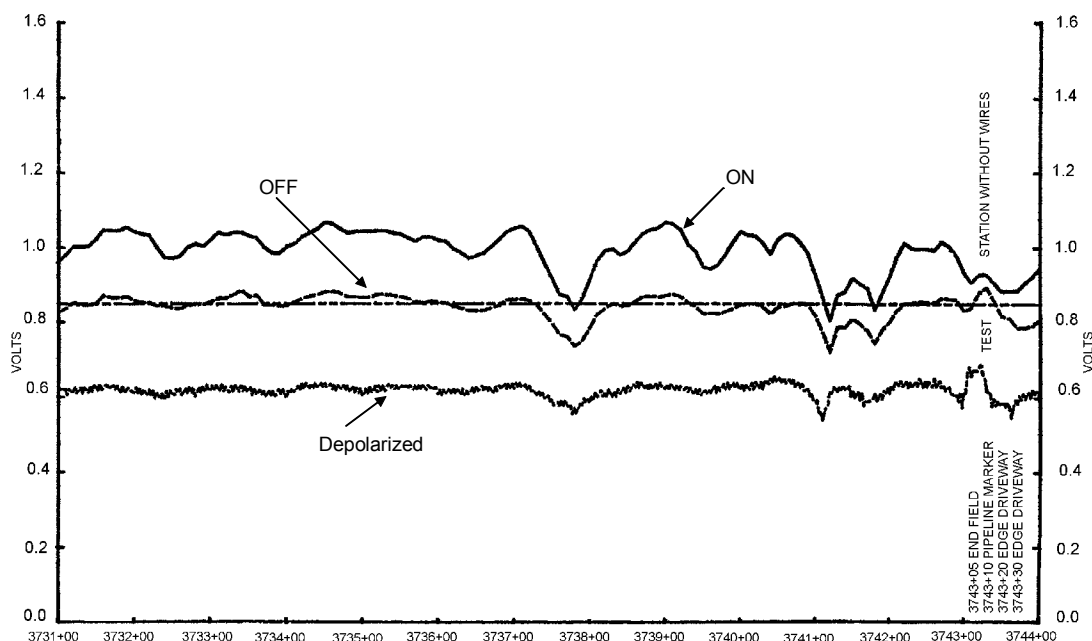


Figure 6.21 ON/OFF Close Interval Survey Showing a Depolarized Potential

Analysis of Surface Potential Surveys

Surveys on Cathodically Protected Structures

The completed pipe-to-electrolyte potential data can be plotted on a graph versus distance for ease of viewing (Figures 6.22 and 6.23). Often, a line is drawn across the graphed pages to easily identify the $-0.850 \text{ V}_{\text{CSE}}$ cathodic protection criteria. A structure-to-electrolyte potential plot where the pipe meets the cathodic protection criterion will have all of the structure-to-electrolyte potentials more negative than the line drawn at $-0.850 \text{ V}_{\text{CSE}}$ (if that is the criterion). If the 100 mV polarization criteria is being used, then the polarized potentials will be 100 mV more negative than the static (native or depolarized) structure-to-electrolyte potential profile (Figure 6.21). Alternately, plot the actual polarization.

Figure 6.22 is data collected using a twelve-second ON and three-second OFF interruption cycle on a pipeline with approximately 300 mV of IR drop. On this section of pipe the OFF potentials are all less negative than $-0.850 \text{ V}_{\text{CSE}}$ indicating adequate levels of cathodic protection do not exist. The polarized potentials in Figure 6.23 are less electronegative than the $-0.850 \text{ V}_{\text{CSE}}$ for the last half. High electronegative potentials through the first half suggest that all current sources may not have been interrupted.

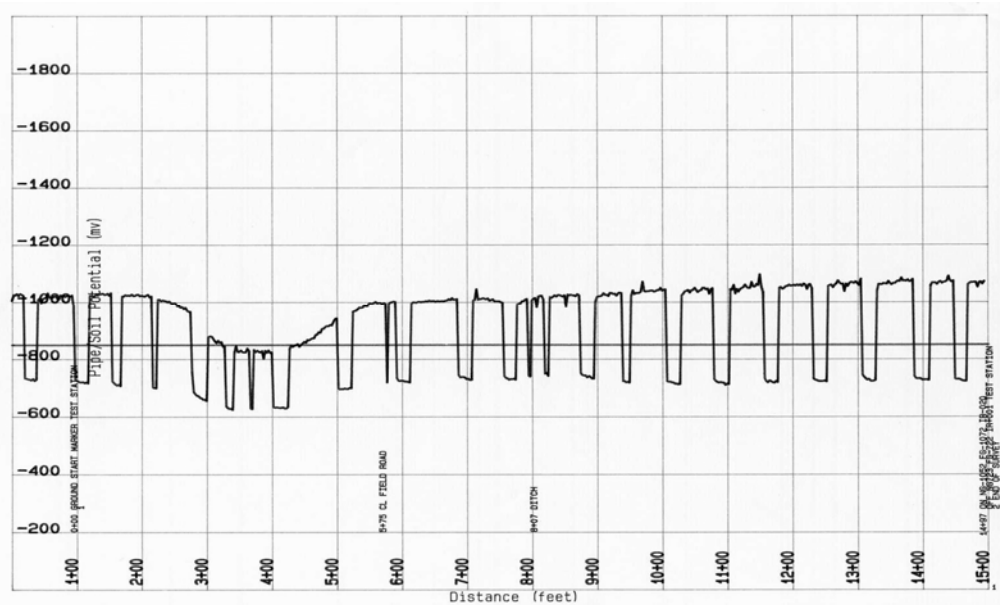


Figure 6.22 On/Off Potential Survey
(Raw data from Datalogger using a Walking Electrode Method)

Figure 6.23 is data collected using a three-second ON and one-second OFF cycle but graphed such that the ON and OFF potentials are separate lines on the plot. Of interest is how the pipe-to-electrolyte potentials change dramatically from having adequate levels of cathodic protection to having inadequate levels and nearly zero IR drop in the ON potential.

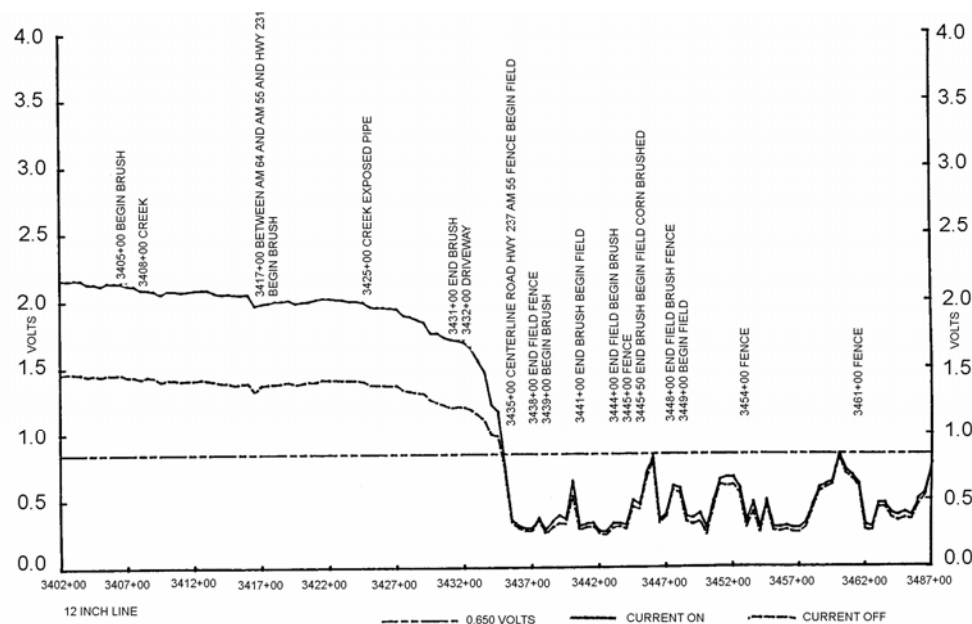


Figure 6.23 ON/OFF Potential Survey Plotted as Two Separate Lines

Figure 6.24 contains data collected on a pipeline with distributed impressed current anodes alongside the pipeline. Again the data was plotted using separate lines for the ON and OFF potentials. The very negative ON potential peaks reveal the locations of the distributed anodes while one can see the OFF potentials in between the anodes are less negative than $-0.850 \text{ V}_{\text{CSE}}$.

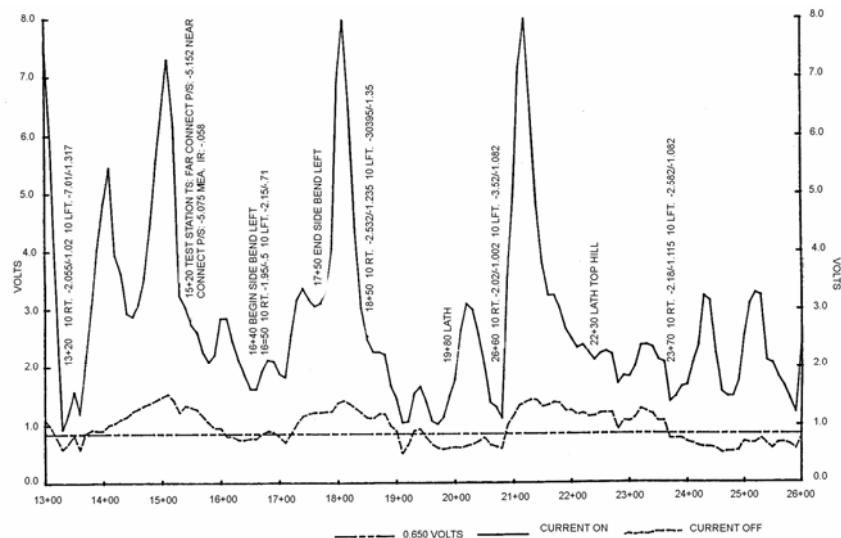


Figure 6.24 ON/OFF Potential Survey Conducted on a Pipeline with Distributed Anodes

Figure 6.25 illustrates data graphed on a larger scale, in this case, 1 in. = 0.50 km, such that 5 km of data fits on a single page. This “big picture” plot may assist in the analysis of pipe-to-electrolyte potentials indicating stray current interference, an electrical short, or inadequate cathodic protection levels.

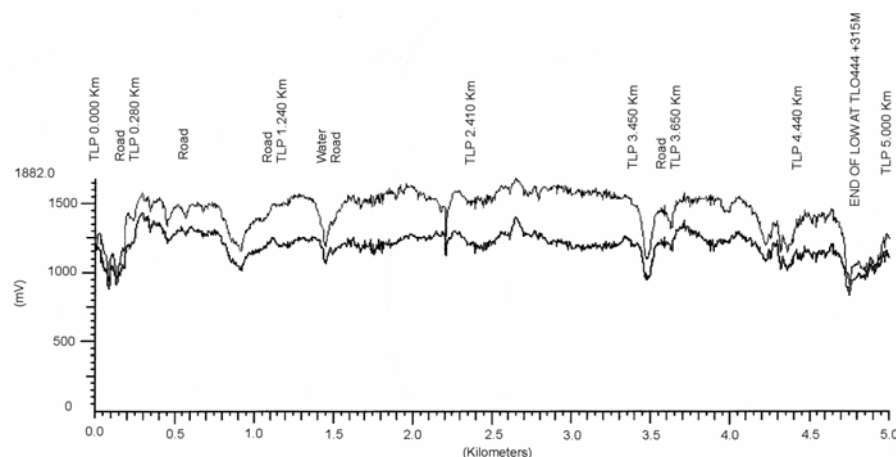


Figure 6.25 ON/OFF Potential Survey on Larger Scale

Lateral/Side Drain Surface Surveys

An additional field test often completed during CIS projects on non-cathodically protected pipes is referred to as a lateral or side drain survey. As structure-to-electrolyte potentials are measured and recorded directly above the pipeline, structure-to-electrolyte potentials are also measured and recorded laterally or to the side of the pipe on one or both sides. The distance is typically 3 m (10 ft) and 7.5 m (25 ft) perpendicular to the pipe.

The benefit of recording this information is that it can be difficult to analyze and draw conclusions from the data measured directly above a pipeline which is not cathodically protected. Anodic locations can appear as both more negative and less negative anomalies, but when compared to the lateral pipe-to-soil potentials, a conclusion can be drawn as anodic locations will only be those areas where the lateral potentials are less negative than the over-the-pipe potentials. Examples of this data can be found in the analysis portion of this chapter.

Current Measurement

Measuring current in the cathodic protection circuit is a necessary procedure in evaluating system performance. Typical current measurements are:

- galvanic anode current
- impressed current system output currents
- current in the structure
- bond current

Both direct and indirect methods of current measurement are available. A direct measurement involves inserting an ammeter into the cathodic protection circuit as illustrated in Figure 6.26.

Using an Ammeter to Measure Current

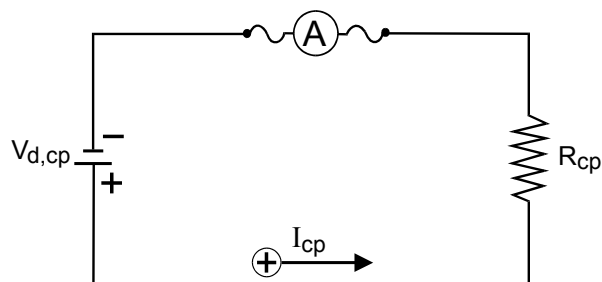


Figure 6.26 Measurement of CP Current Using an Ammeter

An electronic ammeter is typically composed of a voltage measuring device that measures the voltage drop across a low-resistance internal shunt. Ideally, an ammeter should have a low input resistance compared to the circuit resistance (i.e., $R_m \ll R_{cp}$) to prevent measurement error.

For example, in Figure 6.26 from Ohm's law:

$$I_{cp} = \frac{V_{d,cp}}{R_{cp}} \quad \text{Eq. 6-6}$$

but with the ammeter inserted in the series circuit, the current measured on the ammeter (I_m) is given by:

$$I_m = \frac{V_{d,cp}}{R_{cp} + R_m} \quad \text{Eq. 6-7}$$

Hence, the measured current (I_m) will be less than I_{cp} , depending on the resistance of the ammeter.

In many digital multimeters when the mA scale is selected, the ammeter circuit has an input resistance of several ohms. This can lead to significant errors if the ammeter is used to measure the current from a galvanic anode.

Even if a 10 A or 20 A scale is chosen, the input resistance, which may be as low as 0.1 Ω , may still be too high to produce an accurate current measurement

in some circumstances. For instance, if the ammeter is placed in series with a negative drain cable in a parallel set of drain cables, as shown in Figure 6.27, an appreciable error can occur.

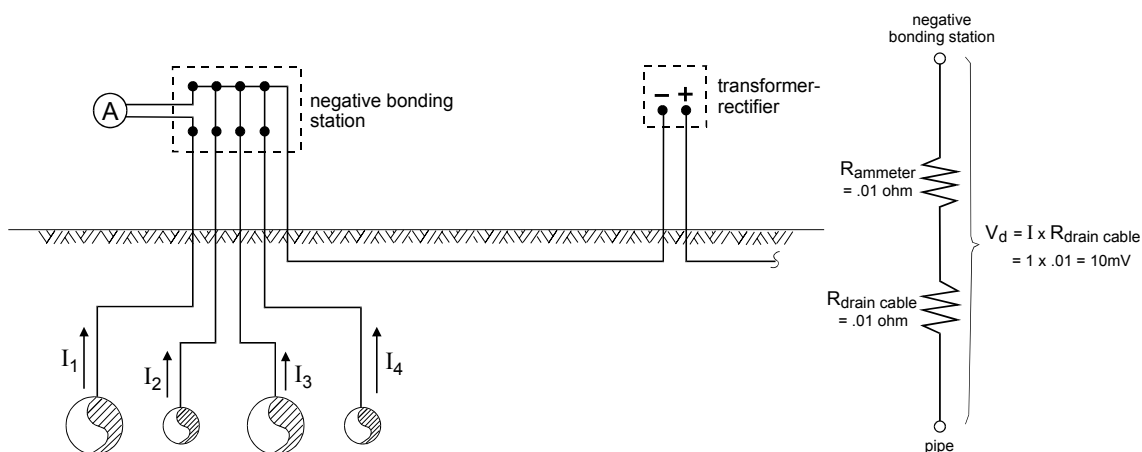


Figure 6.27 Current Measurement in Parallel Drain Conductors

If the shunt resistance inside the ammeter is $0.01 \, \Omega$ and the resistance of the negative return cable is $0.01 \, \Omega$, insertion of the ammeter has doubled the negative return resistance and possibly reduced the return current (I_1) by half.

In both the above examples a more accurate method is to install an appropriately rated shunt permanently in each circuit and simply measure the voltage drop across the shunt and calculate the current. (see the Shunt Table in the *CP Technician Practical Exam Reference Sheet* provided at the back of the course manual).

Using a Shunt to Determine Current Magnitude

In the parallel negative drain cable example, a shunt of the same rating, hence the same resistance, should be installed in series with each negative drain cable as illustrated in Figure 6.28.

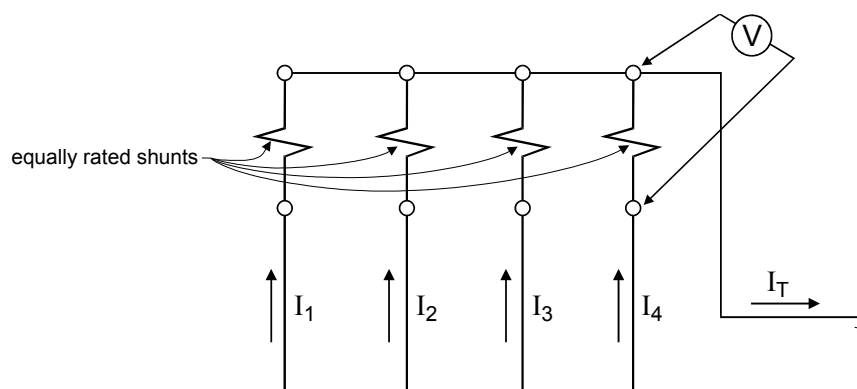


Figure 6.28 Use of Shunts for Current Measurements in Parallel Conductors

When selecting a shunt, its current rating must exceed the anticipated circuit current, and the millivolt drop at the anticipated operating current should be easily measurable on a standard digital multimeter.

For instance, if a shunt rated at 5 A, 50 mV is placed in series with a galvanic anode having an output of 5 mA, the voltage drop across the shunt will be:

$$V_{\text{shunt}} = I_{\text{cp}} \times R_{\text{shunt}} \quad \text{Eq. 6-8}$$

$$= 5 \text{ mA} \times \frac{V_{\text{rating}}}{I_{\text{rating}}}$$

$$= 5 \text{ mA} \times \frac{.050 \text{ V}}{5 \text{ A}}$$

$$V_{\text{shunt}} = 0.05 \text{ mV}$$

This small shunt voltage drop is below the resolution of most digital voltmeters used in the field. For a 5 mA current, a shunt resistance of at least 1 Ω is more appropriate. (See the Shunt Table in the *CP Technician Practical Exam Reference Sheet* provided at the back of the course manual.)

Zero Resistance Ammeter

Sometimes the currents are so small (e.g., < 0.1 mA) they cannot be measured accurately without using very-high-resistance shunts, which can alter the

current magnitude because of their resistance. An example is the measurement of coupon current as illustrated in Figure 6.29.

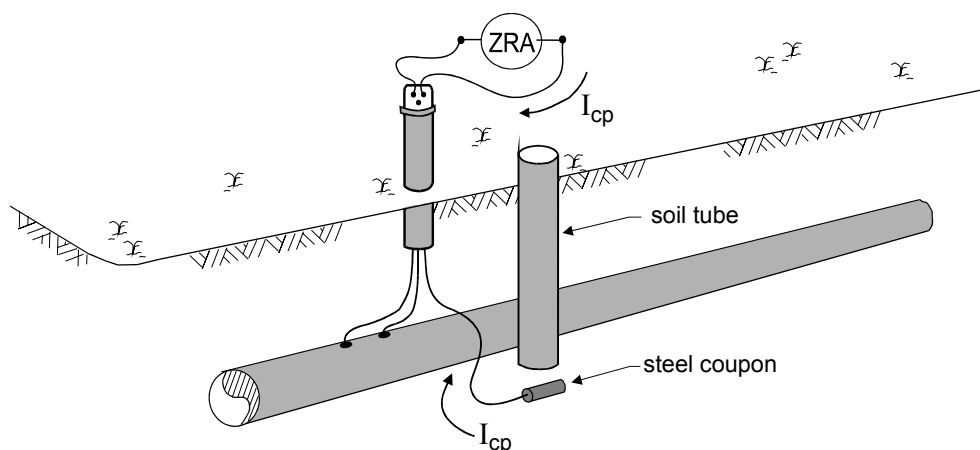


Figure 6.29 Current Measurement Using a Zero Resistance Ammeter (ZRA)

If the coupon has a surface area of 10 cm^2 and a current density of $10 \text{ } \mu\text{A}/\text{cm}^2$ the coupon current (I_{cp}) would be:

$$I_{cpn} = 10 \text{ } \mu\text{A}/\text{cm}^2 \times 10 \text{ cm}^2$$

$$I_{cpn} = 100 \text{ } \mu\text{A} \text{ or } 0.1 \text{ mA}$$

Measurement of such a small current with an ammeter would introduce several ohms of resistance into the circuit as would a shunt since a resistance of $100 \text{ } \Omega$ is required to measure in the 10 mV range. Under these circumstances, a zero resistance ammeter should be used.

Clamp-On Ammeter

A relatively noninvasive method of measuring current in a conductor is by using a clamp-on ammeter as illustrated in Figure 6.30.

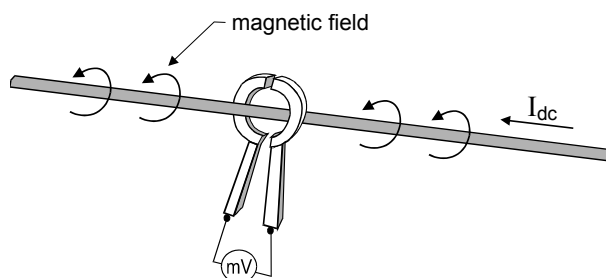


Figure 6.30 Using a Clamp-On Ammeter to Measure Current

The clamp-on ammeter contains a “Hall effect” device that produces a voltage output proportional to the strength of the magnetic field, which is proportional to the magnitude of the current in the conductor.

The Hall effect is illustrated in Figure 6.31 for a fixed meter current (I_m). As electrical charges move perpendicular to the magnetic field (B), a lateral force is exerted on the charges causing a potential difference to appear across the sides of the copper plate.

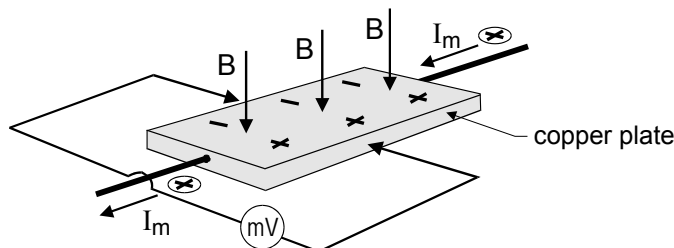


Figure 6.31 Schematic of the Hall Effect for Conventional Current Direction

The magnitude of this voltage is proportional to the magnetic field (B), which in turn is dependent on the magnitude of the current (I_{dc}) in the conductor.

Accuracy of the clamp-on ammeter diminishes at currents of a few mA. When there are multiple current-carrying conductors in a congested area, the accuracy is reduced if there is magnetic interference from adjacent conductors.

Pipeline Current Measurements

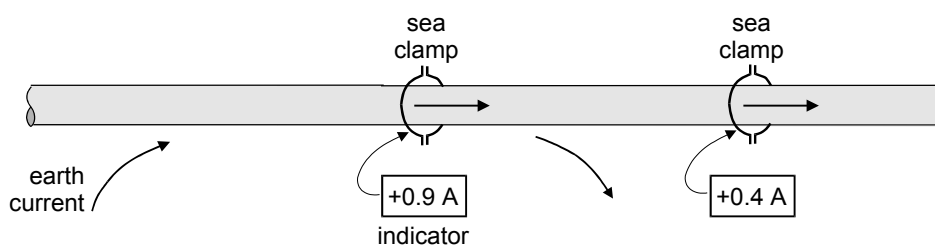
Uses

Pipeline current measurements are used to detect stray current and electrical shorts, and establish current distribution from temporary or permanent cathodic protection

systems. Current can be measured by a clamp-on ammeter or by using a section of pipeline of known resistance as a shunt.

Use of a Clamp-On Ammeter

An illustration of the use of clamp-on ammeters is given in Figure 6.32.



Earth current leaving subject pipeline is $0.9 - 0.4 = 0.5$ A.

Figure 6.32 Pipe Current Measurement Using Sensing Loop and Swain Meter

Source: Swain, W.H., *Clamp-On Ammeters Can Watch Cathodic Protection Current Flow*,
Pipe Line & Gas Industry, March 1998, p.38

2-Wire Line Current Test

Current flow on a pipeline is measured by means of an IR drop or calibrated test station such as shown in Figure 6.33 or by using test stations and aboveground appurtenances as a temporary IR-drop test station. In an IR-drop test, the pipe simulates a low-resistance shunt. When properly calibrated, a voltmeter can be used to measure a voltage drop between the two wires or connection points to the pipe. Using Ohm's Law, the current flowing in the pipeline steel can be calculated.

A 2-wire test point span can be used where a known length of pipeline and the diameter and wall thickness or the weight per foot are known. The current flow in the pipe span can be calculated by measuring the voltage drop across the span, determining the resistance of the span from a pipe table, and using Ohm's Law as you would with a shunt. Figure 6.33 shows the test setup to measure the mV drop in the section of pipeline.

Table 6.1 provides some resistance values for common pipe sizes. The section of pipe must be continuous with the same diameter and wall thickness without attachments through the pipe span to be used.

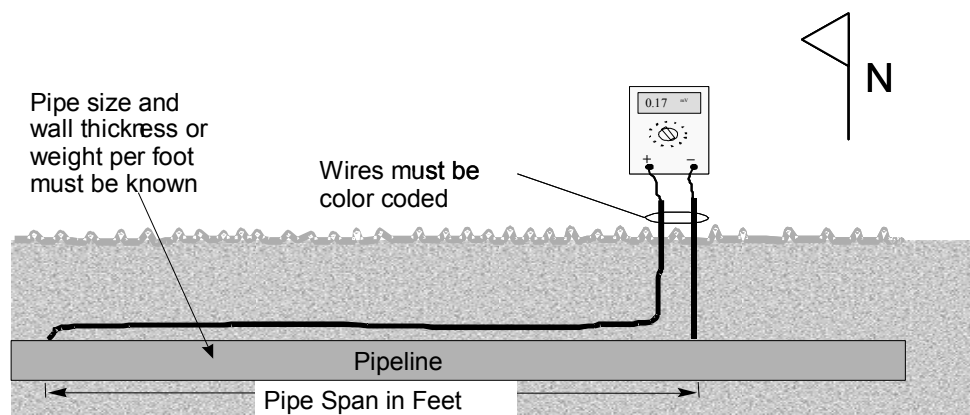


Figure 6.33 2-Wire Line Current Test

Because the voltage drop across a pipe span is relatively small, with earlier instruments it was necessary to correct for the voltage drop in the test leads caused by the current drawn by the meter. However, with the high-input resistance meters available today, this correction is not necessary.

For example, if the voltage drop across a 200-ft (61-m) span of 30-in. (762 mm) pipe weighing 118.7 lbs/ft (176.65 kg/m) is 0.17 mV, then current flow is calculated as follows:

Pipe resistance/ft from Table 6.1	$= 2.44 \mu\Omega / \text{ft} \ (8.01 \mu\Omega / \text{m})$
	$= 0.00000244 \ \Omega / \text{ft}$
	$\ (0.00000801 \ \Omega / \text{m})$
Total resistance	$= 200 \ \text{ft} \times 0.00000244 \ \Omega / \text{ft}$
	$= 0.000488 \ \Omega$
	OR $= 61 \ \text{m} \times 0.00000801 \ \Omega / \text{m}$
	$= 0.000488 \ \Omega$
Measured voltage drop	$= 0.17 \ \text{mV}$
Current (I) = $\frac{E}{R}$	$= \frac{0.00017 \ \text{V}}{0.000488 \ \Omega}$
	$= 0.348 \ \text{A}$

Table 6.1 Table of Pipe Resistances**Steel Pipe Resistance*(A)(B)**

Pipe Size in.	Outside Diameter		Wall Thickness		Weight		Resistance	
	in.	cm	in.	cm	lb/ft	kg/m	$\mu\Omega/\text{ft}$	$\mu\Omega/\text{m}$
2	2.35	5.97	0.154	0.39	3.65	5.43	76.2	256.84
4	4.5	11.43	0.237	0.60	10.8	16.07	26.8	87.93
6	6.62	16.81	0.280	0.71	16.0	28.28	15.2	46.87
8	8.62	21.89	0.322	0.82	28.6	42.56	10.1	33.14
10	10.75	27.31	0.365	0.93	40.5	60.27	7.13	23.39
12	12.75	32.38	0.375	0.95	46.6	73.81	5.82	16.09
14	14.00	35.56	0.375	0.95	54.6	81.26	5.29	17.36
16	16.00	40.64	0.375	0.95	62.6	93.16	4.61	15.12
18	18.00	45.72	0.375	0.95	70.6	105.07	4.09	13.42
20	20.00	50.80	0.375	0.95	78.6	116.97	3.68	12.07
22	22.00	55.88	0.375	0.95	86.6	128.88	3.34	10.96
24	24.00	60.96	0.375	0.95	94.6	140.78	3.06	10.04
26	26.00	66.04	0.375	0.95	102.6	152.69	2.82	9.25
28	28.00	71.12	0.375	0.95	110.6	164.59	2.62	8.60
30	30.00	76.20	0.375	0.95	118.7	176.65	2.44	8.01
32	32.00	81.28	0.375	0.95	126.6	188.41	2.28	7.48
34	34.00	86.36	0.375	0.95	134.6	200.31	2.15	7.05
36	36.00	91.44	0.375	0.95	142.6	212.22	2.03	6.66

*Conversions: 1 in. = 2.54 cm

1 ft = 0.3048 m

(A) Based on steel density of 489 lbs/ft³ (7832 kg/m³) and steel resistivity of 18 $\mu\Omega\text{-cm}$.(B) $R = \frac{16.061 \times \text{resistivity in } \mu\Omega\text{-cm}}{\text{Resistance of 1 ft of Weight per foot pipe, } \mu\Omega}$

Refer again to Figure 6.33. Note the meter is showing a positive indication. This means the current is entering the meter on the positive terminal. The positive terminal is connected to the west end of the span. Since the meter is in parallel with the span, current flow on the pipe is from west to east.

The accuracy of this test method depends greatly on accurate knowledge of the dimensions of the pipe. Should there be an odd-sized joint within the span, or some appurtenance such as a valve, the calculated resistance will not be correct. The 4-wire test method overcomes these difficulties.

4-Wire Line Current Test

Pipeline current can also be measured using the four-wire span illustrated in Figure 6.34. For accurate measurement, the span is calibrated by injecting a known DC test current through the pipe using the outside test leads ① and ④ and measuring the resulting voltage drop across test leads ② and ③.

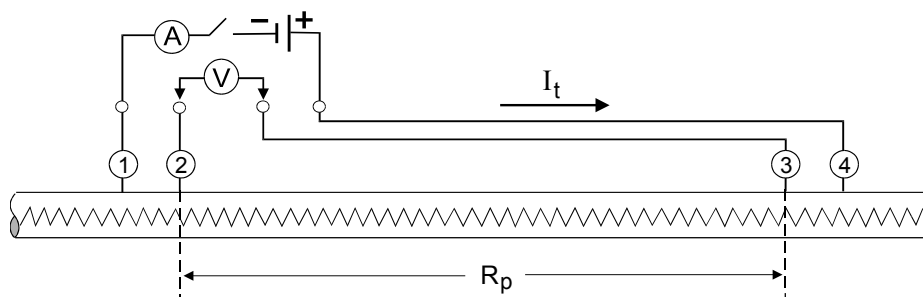


Figure 6.34 Calibrating a Pipeline Current Span

The resistance of the pipe between test leads ② and ③ is calculated from Ohm's law:

$$R_p = \frac{\Delta V_{2-3}}{\Delta I_t} \quad \text{Eq. 6-9}$$

The result can be anticipated prior to the test by referring to Table 6.1.

Attention to polarity is important in this measurement since there will probably be a residual current during the test, and the test current may cause a reversal in the voltage drop polarity.

For example,

$$\begin{aligned} V_{2-3} &= +21 \text{ mV (before test current applied)} \\ V_{2-3} &= -19 \text{ mV (after test current applied)} \\ I_t &= 10 \text{ A} \end{aligned}$$

The resistance (R_p) of the pipe section being tested is:

$$R_p = \frac{+21 \text{ mV} - (-19 \text{ mV})}{10 \text{ A}}$$

$$R_p = \frac{+40 \text{ mV}}{10 \text{ A}} = 4 \text{ m}\Omega$$

The calibration factor is calculated as follows:

$$K = I_{\text{test}} / \Delta E_{\text{test}} \quad \text{Eq. 6-10}$$

where:

K = calibration factor of pipe section (A/mV)

I_{test} = test current applied to section (A)

ΔE_{test} = E with current applied – E with no current applied (mV)

Therefore the current calibration factor is: $\frac{4 \text{ mV}}{\text{A}}$

and the residual current magnitude is:

$$I_{\text{residual}} = 21 \text{ mV} \times \frac{0.25 \text{ A}}{\text{mV}} = 5.25 \text{ A}$$

with a direction from 2 to 3.

Normally, if the pipeline operating temperature is stable, this need only be done once as the calibration factor will remain the same for subsequent tests at the same location. On pipelines where the temperature of the pipe changes considerably (with accompanying changes in resistance), more frequent calibration may be necessary.

Once the calibration factor is known, the normal current magnitude can be calculated. First, measure the voltage drop in mV across the measuring span (without the battery current) using the inside test wires. This voltage drop is due to normal pipeline current.

Calculate current flow by multiplying the calibration factor by the voltage drop measured above:

$$I = K \times \Delta E \quad \text{Eq. 6-11}$$

where:

I = pipeline current (A)

K = calibration factor of pipe

ΔE = voltage drop of pipe section (mV)

The polarity of the voltage drop will determine the direction of current flow. If the voltage drop reading is positive, then the direction of current flow is from the positive to the negative terminal of the voltmeter. If the reading is negative, then the direction of current flow is from the negative to the positive terminal.

Most digital meters will not read below 0.1 mV. If readings below 0.1 mV are anticipated, or if a zero reading is obtained during a test, a more sensitive meter must be used.

Earth Current Measurements (see also Chapter 7)

A series of potentials measured between two reference electrodes can indicate current flow and its direction in the earth, as shown in Figure 6.35. This type of measurement is sometimes used to determine if current is flowing toward or away from a structure. Direction of current flow is from the positive electrode towards the negative electrode if the value displayed on the voltmeter is positive.

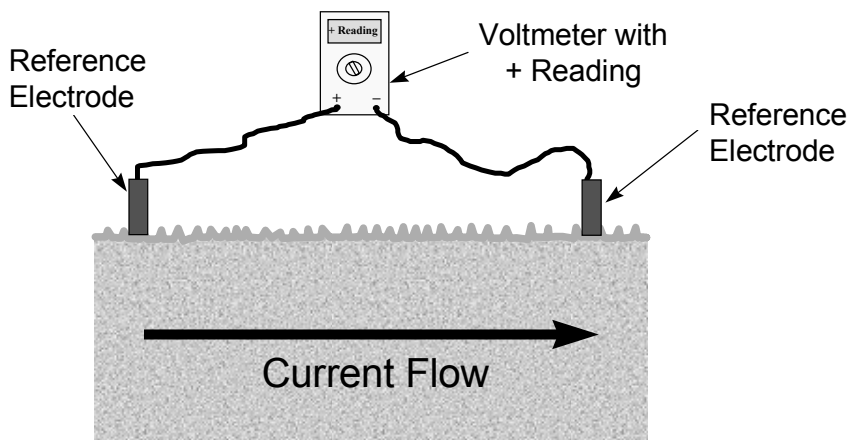


Figure 6.35 Potential Measurement Between Two Reference Electrodes

Non-Cathodically Protected Structures

On lines that are not cathodically protected, corroding areas, or “hot spots,” can be found where the potentials are more negative than the nearby potentials. This is opposite of a cathodically protected structure and is often confusing. In addition, it

is beneficial to complete a pipe-to-soil potential survey laterally or to the side of the pipeline. Often, this distance is 15 to 25 ft to one or both sides of the pipe. These surveys are completed on bare unprotected pipelines and pre-stressed concrete cylinder pipe (PCCP).

Figure 6.36 illustrates an example of stray current interference as detected by an over-the-line and lateral pipe-to-soil potential survey. In this example, one area of current discharge was found. Stray current interference is identified when the over-the-line potential becomes positive in relation to nearby potentials and the lateral potential is more positive than the over-the-line potentials. This area should be analyzed to determine if corrective action in the form of cathodic protection or mitigation bonds should be used. Stray current control is discussed in Chapter 7 “Stray Current and CP Interference.”

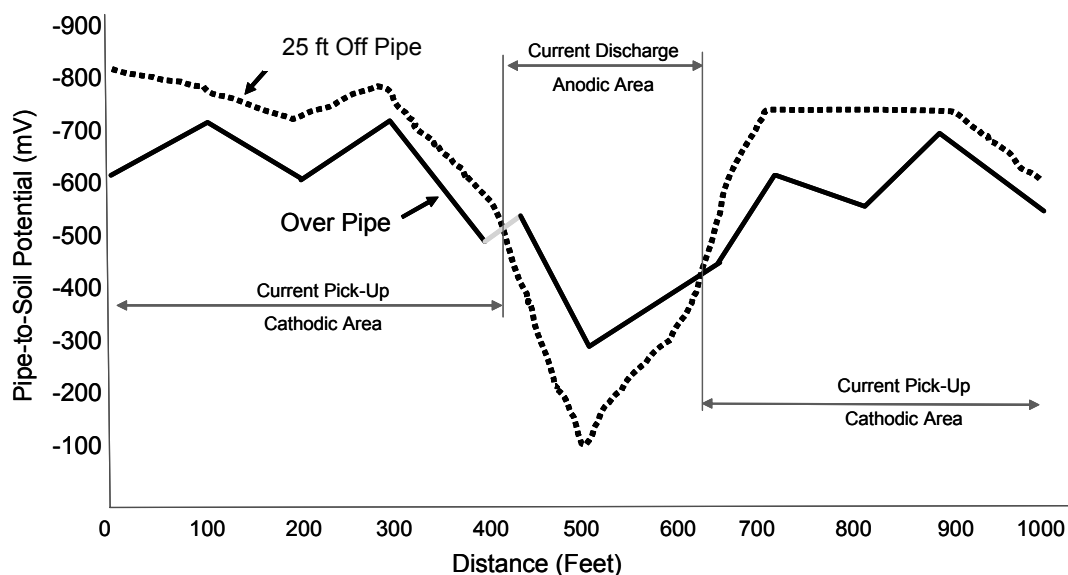


Figure 6.36 Potential Profile of Pipe Subject to Exposure from Cathodic Protection Interference

Figure 6.37 illustrates the type of data that would be seen where galvanic corrosion activity is affecting a non-cathodically protected pipe.

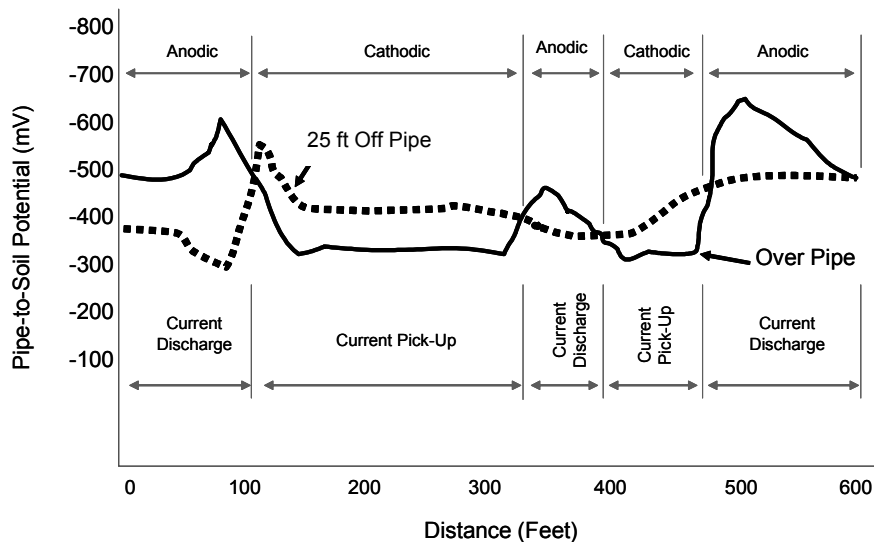


Figure 6.37 Potential Profile of Pipe Subject to Galvanic Corrosion Activity

The anodic areas are those locations where the over-the-line potentials become more negative with respect to nearby potentials and when the potentials away from the pipe (lateral) are less negative than the over-the-line potentials. The cathodic areas of the pipe are where the lateral potentials are more negative than the over-the-line potentials. The exact location of each anodic area can be defined by repeating the survey over that area while progressively decreasing the spacing of the electrodes and taking measurements to both sides.

Figure 6.38 illustrates a close interval survey completed above and laterally to the pipe where a bimetallic couple exists. The over-the-line potential becomes less negative with respect to nearby potentials and the lateral potentials are less negative than the over-the-line potentials.

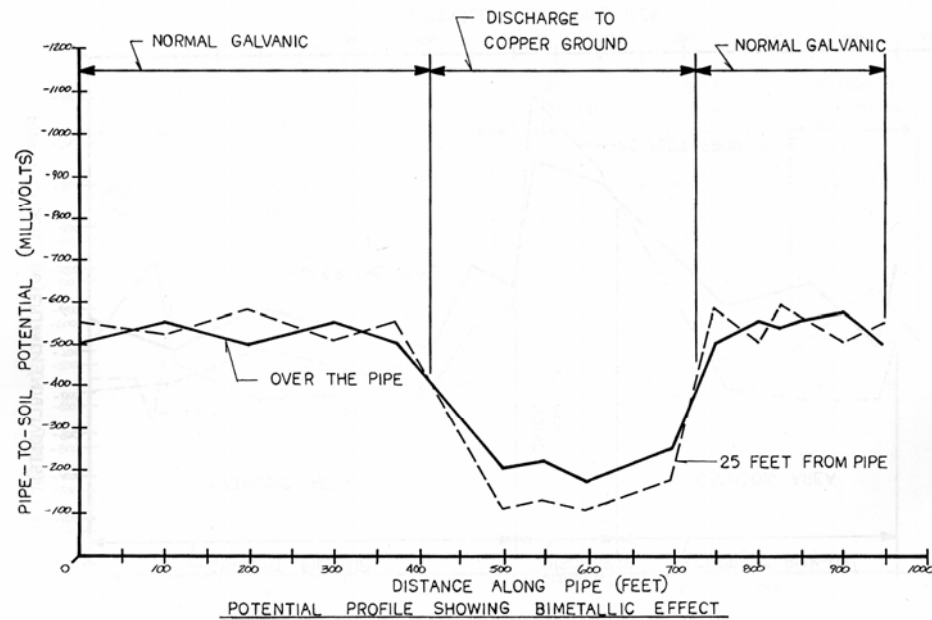


Figure 6.38 Potential Profile Showing Bimetallic Effect

Surface Coating Evaluation Techniques on Buried Pipelines

This section will discuss the various techniques used to evaluate the condition of pipeline coatings once buried. These techniques are:

- Pearson Survey
- DCVG Survey
- Pipeline Current Mapper
- Coating Resistance

Pearson Survey

A Pearson Survey is a method used to detect holidays in a pipe coating after the pipe is buried. In this method, an AC audio signal is impressed onto the pipe using a transmitter. The transmitter is connected to the pipeline (making it a conductive locator) and to a temporary ground. The better the ground, the stronger the signal. Two individuals, each having grounding spikes attached to their shoes, walk directly over the line. The individuals are electrically connected together and one carries a radio receiver. As the location of the coating holiday is reached, the radio signal becomes stronger on the receiver. As

the two individuals continue walking, the signal will then “null” and when the back or second person approaches the holiday, the signal will again peak. The point of the “null” is the location of the coating holiday. Figure 6.39 shows this method schematically.

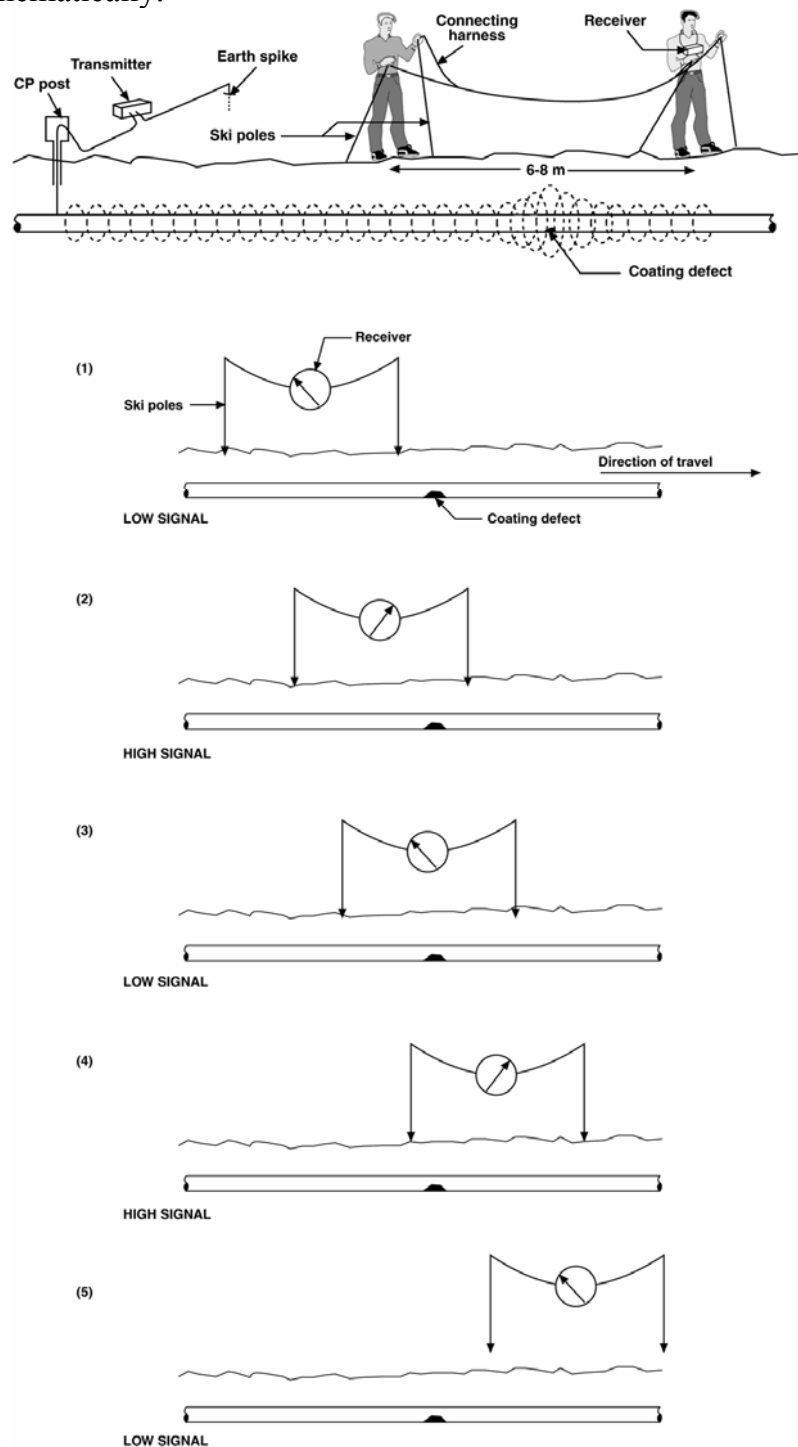


Figure 6.39 Illustration of Pearson Method of Holiday Detection

Direct Current Voltage Gradient (DCVG) Survey

DCVG is a method for detecting cathodic protection current pickup at coating holidays. The DCVG system consists of an analog strap-on voltmeter, connection cables, and two probes with electrodes filled with water. This technique is accomplished by installing a current interrupter in an existing rectifier unit or by using a temporary CP system. The interrupter is installed in series in either leg of the DC output of the rectifier or by installing it in the AC circuit. The interrupter is set to cycle at a very fast rate with the ON period less than the OFF period, such as a 1/3 second ON and 2/3 second OFF. This short cycle allows for a quick deflection measurement by the analog voltmeter (Figure 6.40).



Figure 6.40 DCVG Survey

The analog voltmeter (Figure 6.41) is a very sensitive meter with the ability to adjust the input impedance and the scale with which the meter is displaying the data. Deflections of less than 1 mV are easily noticeable on this voltmeter. In addition, the needle has the ability to deflect in both the positive and negative directions from the zero point which assists in determining the direction the current is flowing in the soil.



Figure 6.41 Analog Voltmeter

The survey method consists of measuring the “ON” and “OFF” potentials at all encountered test points, valves, and risers to determine the signal strength (i.e., difference between ON and OFF readings). The numerical potential difference is the signal strength. An example can be seen below.

ON potential	=	-1.45 V
OFF potential	=	-0.95 V
Signal Strength	=	1.45 - 0.95 V
	=	0.5 V or 500 mV

While walking along the pipeline route the probes are used as walking sticks making sure one electrode tip is in contact with the ground at all times. One probe is always kept near the pipeline centerline while the other is held laterally at 1 to 2 m. Where there is no coating defect, the analog voltmeter needle does not register movement. When a coating defect is approached a noticeable swing can be observed on the voltmeter at the same rate as the interrupter switching cycle. The amplitude of the needle swing will increase as the defect is approached and decreases when passed. The estimated signal strength can be illustrated by using the data represented in Figure 6.42 where:

Signal strength at TS A	=	200 mV
Signal strength at TS B	=	300 mV
Defect from TS A	=	1,500 yds (1,372 m)
Defect from TS B	=	500 yds (457 m)

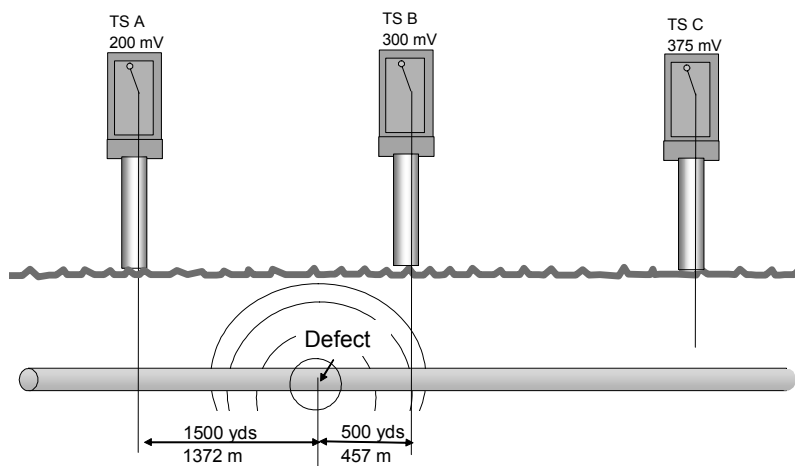


Figure 6.42 Signal Strengths

Estimated signal strength at defect:

$$S_D = S_A + \left[\left(\frac{d_A}{d_A + d_B} \right) (S_B - S_A) \right] \quad \text{Eq. 6-12}$$

where:

S_D = signal strength at defect (mV)

S_A = signal strength at Point A (mV)

S_B = signal strength at Point B (mV)

d_A = distance from A

d_B = distance from B

$$\begin{aligned} S_D &= 200 \text{ mV} + \frac{1500 \text{ yds}(1372 \text{ m})}{1500 \text{ yds}(1372 \text{ m}) + 500 \text{ yds}(457 \text{ m})} (300 \text{ mV} - 200 \text{ mV}) \\ &= 275 \text{ mV} \end{aligned}$$

A straight-line attenuation effect is assumed between test locations to calculate the signal strength at intermediate defect locations.

Centering the defects is achieved by marking the approximate location of the defect at the area where the maximum amplitude is indicated. At two separate locations (A and B in Figure 6.43), offset from the line by approximately 4 m, the probes are placed along the voltage gradient to obtain a null (zero) on the meter. A right-angle line through the center of the probe locations will pass over the coating defect epicenter. This geometrical procedure repeated on opposite sides of the pipeline will locate the exact point above the defect. This procedure is illustrated in Figure 6.43.

Having detected the epicenter of the coating defect, a series of lateral readings are measured moving towards remote earth. Lateral readings near the defect will yield maximum voltage differences where gradients are at a maximum. Readings at remote earth will indicate zero to 1 mV deflections. The summation of these readings is commonly referred to as the over-the-line to remote earth voltage. The expression “percentage IR” has been adopted to give an indication of defect size. For instance, if a series of lateral millivolt readings to remote earth are as follows, 25, 15, 6, 4, 3, 1, 1, 0, then the percentage IR can be calculated as follows:

$$\begin{aligned}
 \text{Pipe-to-Remote Earth} &= \Sigma \text{Earth Gradients} \\
 &= 25+15+6+4+3+1+1 \text{ mV} \\
 &= 55 \text{ mV}
 \end{aligned}$$

$$\text{Percentage IR} = \frac{\text{Pipe-to-remote earth} * 100\%}{\text{Signal strength at defect}} \quad \text{Eq. 6-13}$$

$$= \frac{55 \text{ mV}}{275 \text{ mV}} * 100 = 20\%$$

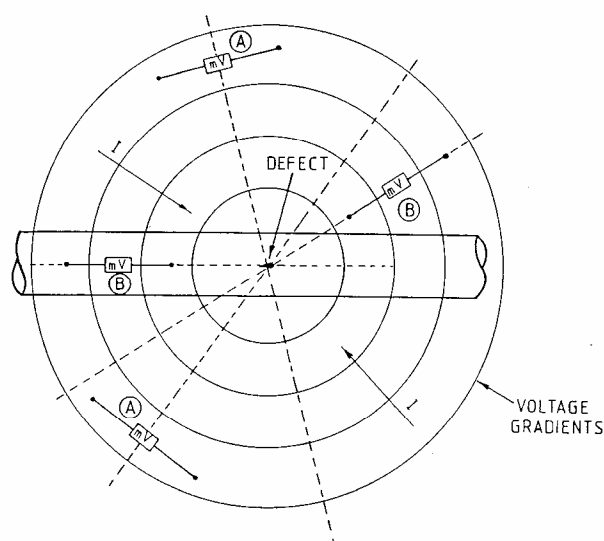


Figure 6.43 Voltage Gradients

Theoretically, this percentage IR is used to predict the reduction in protection levels ignoring polarization effect. Therefore, knowing the ON potential of the pipeline system one can multiply the percentage IR by the known potential to get the theoretical structure-to-electrolyte potential reading of the defect area.

Pipeline Current Mapping

Pipeline current mapping is a method of evaluating and mapping cathodic protection current pickup. It was developed to non-intrusively and accurately measure a near DC current temporarily impressed on the structure and therefore distributed along the pipeline. The PCM system consists of a two-part system; a portable transmitter that applies a special near-DC signal to the pipeline and a hand-held receiver that locates and displays the current magnitude and direction of the near DC signal. If the mainline or repair coatings are damaged causing holidays, or if there is an electrical contact between the pipeline and another metallic structure, this will result in a sufficient pickup of the induced near-DC signal. This is illustrated in Figure 6.44.

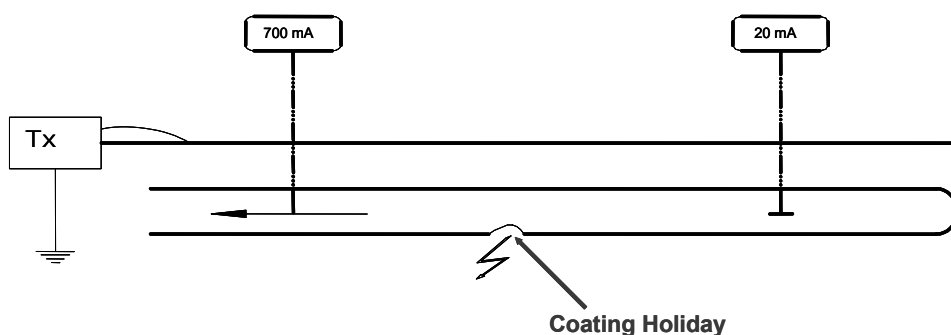


Figure 6.44 Current Pickup

Coating Resistance Calculations

Coating resistance measurements are a means of establishing a coating's ability to provide a dielectric barrier between the structure and the environment. The better barrier a coating provides the higher the coating resistance. The coating resistance is simply the resistance of the structure to the environment multiplied by the surface area of the structure. Units are therefore $\Omega\text{-ft}^2$. Coating resistance measurements years apart can reveal the long-term performance of a coating and if anything has occurred that detrimentally affected the overall structure coating (e.g., electrical shorts, construction damage, and abnormal soil stress).

Test data are obtained from the pipeline section under investigation which can be of any length, though typically three to five miles in length. Pipe-to-electrolyte potential readings (with current ON and OFF) and line current measurements are obtained using an interrupter to cycle the nearest rectifier or a temporary power source. The resistance of the pipe section is calculated and the

coating resistance calculated with the known pipe surface area. For example (see Figure 6.45):

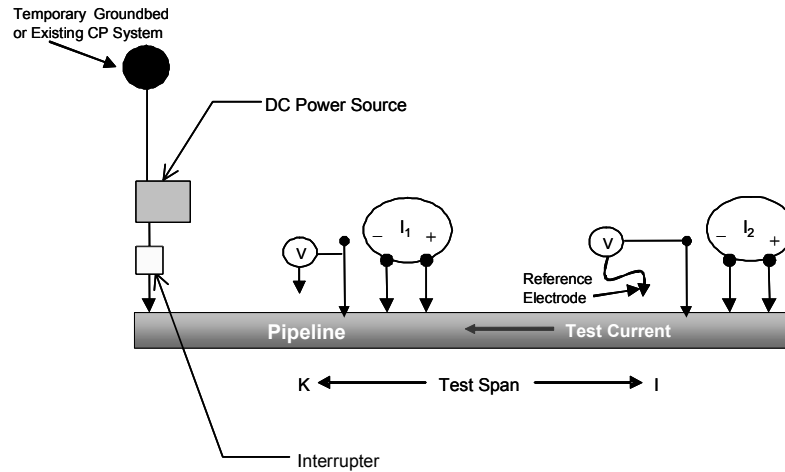


Figure 6.45 Set-Up for Coating Resistance Measurement

Assume the following field data:

Size of Pipe: 24-in. dia. (610 mm, 61 cm or 0.61 m)

Length of Test span: 1 mile = 5,280 ft (1609 m or 1.609 km)

$E_{ON_{TS1}} = -2.00 \text{ V}$
 $E_{OFF_{TS1}} = -0.90 \text{ V}$
 $\Delta E_{TS1} = 2 \text{ V} - 0.9 \text{ V} = 1.10 \text{ V}$

$I_{ON_{TS1}} = 3.00 \text{ A}$
 $I_{OFF_{TS1}} = 0.20 \text{ A}$
 $\Delta I_{TS1} = 3.0 \text{ A} - 0.20 \text{ A} = 2.80 \text{ A}$

$E_{ON_{TS2}} = -1.70 \text{ V}$
 $E_{OFF_{TS2}} = -0.85 \text{ V}$
 $\Delta E_{TS2} = 1.7 \text{ V} - 0.85 \text{ V} = 0.85 \text{ V}$

$I_{ON_{TS2}} = 2.80 \text{ A}$
 $I_{OFF_{TS2}} = 0.10 \text{ A}$
 $\Delta I_{TS2} = 2.80 \text{ A} - 0.10 \text{ A} = 2.70 \text{ A}$

$$\text{Total Pipe Surface Area} = d \times \pi \times L \quad \text{Eq. 6-14}$$

$$= \frac{24 \text{ in}}{12 \text{ in / ft}} \times \pi \times 5,280 \text{ ft} = 33,158 \text{ ft}^2$$

$$\text{Or in metric} = 0.61 \text{ m} \times \pi \times 1,609 \text{ m} = 3080 \text{ m}^2$$

$$\Delta E_{ave} = \frac{\Delta E_{TS1} + \Delta E_{TS2}}{2} \quad \text{Eq. 6-15}$$

$$\Delta E_{ave} = \frac{1.10 \text{ V} + .85 \text{ V}}{2} = 0.975 \text{ Volt}$$

Now that the average potential change caused by the current is known, the current that affects only that section of pipe must be calculated. To accomplish this, the current “entering” the test section is subtracted from the current exiting the test section. It is this value of current that the pipe is picking up in this test section.

$$\begin{aligned} I_C &= \text{current on pipe section of interest} \\ &= \Delta I_{TS1} - \Delta I_{TS2} \\ &= 2.80 \text{ A} - 2.70 \text{ A} = 0.10 \text{ A} \end{aligned} \quad \text{Eq. 6-16}$$

$$\begin{aligned} \text{Pipe-to-earth resistance} &= R_{P/S} = \frac{\Delta E_{ave}}{I_C} \\ &= \frac{0.975 \text{ V}}{0.1 \text{ A}} = 9.75 \Omega \end{aligned} \quad \text{Eq. 6-17}$$

$$\begin{aligned} \text{Specific coating resistance} &= r_{CE} = A_{pipe} \times R_{p/s} \\ &= 33,158 \text{ ft}^2 \times 9.75 \Omega \\ &= 323,294 \Omega\text{-ft}^2 \end{aligned} \quad \text{Eq. 6-18}$$

$$\begin{aligned} \text{Or in metric} \\ r &= 3080 \text{ m}^2 \times 9.75 \Omega \\ r &= 30030 \Omega\text{-m}^2 \end{aligned}$$

An assumption is made that the change in structure potential as a result of the current is linear and that the average change in structure potential over the test span is the average of the beginning and ending test point potential changes. A more representative value might be obtained by averaging multiple structure potential changes measured at various locations along the test span.

When discussing coating resistance, often the terminology “coating conductance” is used. Conductance is the reciprocal of resistance and the units used are typically Siemens (S) or microsiemens (μS).

$$\sigma = \frac{1}{R} \quad \text{Eq. 6-19}$$

where: σ = conductance (S)
R = resistance (Ω)

In the example above: $\sigma_{p/s} = \frac{1}{R_{p/s}} = \frac{1}{9.75\Omega} = 0.102 \text{ S}$

For further information refer to NACE Standard TM0102, “Measurement of Protective Coating Electrical Conductance on Underground Pipelines.”

Current Requirement Tests

When a structure is in place in its final configuration, it is possible to perform current requirement tests. Such tests have the advantage of producing data on the actual structure and its environment and do not involve assumptions as to effectiveness of the protective coating and other factors. Structures which have been designed for the application of cathodic protection can be tested in their entirety or broken down into sections.

Current requirement testing involves installation of either a permanent or test anode system. The purpose is to introduce current into the earth at the site where the permanent cathodic protection system (groundbed) will be located. For large structures, a representative area can be chosen for the initial test phase. A suitable power supply (batteries, test rectifier, or motor generator system) is then connected between the structure and test groundbed as illustrated in Figure 6.46. Test current is applied between the groundbed and the structure and the effects on the structure are measured.

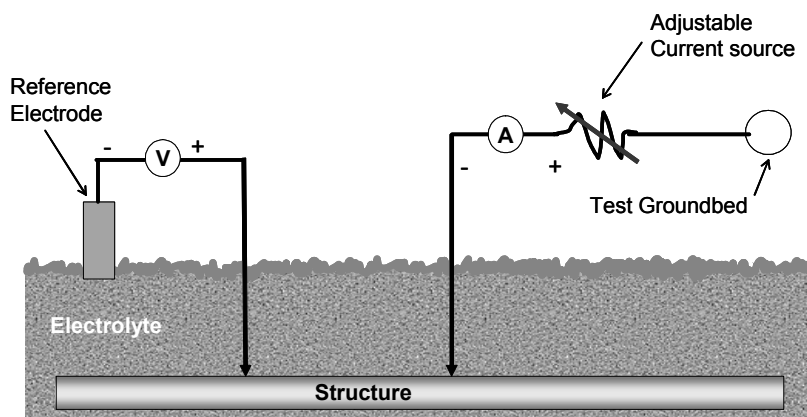


Figure 6.46 Test Circuit for Current Requirement Test

With this circuit, controlled amounts of current can be applied to the structure from the anode.

The potential measured includes the following:

- The electrochemical potential between the structure and the reference electrode
- An “IR drop” produced between the point in the electrolyte where the reference electrode is located and the structure

Calculation:

$$I_{req} = \frac{\Delta E_{preq} * I_{test}}{\Delta E_{ptest}} \quad \text{Eq. 6-20}$$

where:

I_{req} = Estimated current requirement (A)

ΔE_{ptest} = Polarization from test (V) [$\Delta E_{OFF} - \Delta E_{initial}$]

ΔE_{preq} = Polarization required (V)

= [0.850 V – ΔE_{OFF}] for -850 mV_{CSE} polarized potential criterion or [100 mV] for 100 mV polarization criterion

The formulas used for these calculations consider:

The value of resistance producing IR drop

$$R = (E_{ON} - E_{OFF}) / I_{ON} \quad \text{Eq. 6-21}$$

The IR drop can be calculated for other intermediate levels of current using an average value for R:

$$\text{IR drop} = I_{\text{applied}}R$$

Following is an example of a current requirement calculation:

- | | | |
|----|--|-----------------------------------|
| 1. | Static pipe-to-soil potential | $= -0.645 \text{ V}_{\text{CSE}}$ |
| 2. | Desired polarized p/s potential | $= -0.850 \text{ V}_{\text{CSE}}$ |
| 3. | Test current | $= 50 \text{ mA (0.050 A)}$ |
| 4. | Polarization potential due to test current | $= 0.775 \text{ V}_{\text{CSE}}$ |

From Equation 6-20:

$$I_{\text{req}} = \frac{[0.850 \text{ V} - 0.645 \text{ V}] 0.050 \text{ A}}{(0.775 - 0.645)}$$

$$= 0.0788 \text{ A or } 7.88 \text{ mA}$$

Electrical Isolation

Indication of Problems

Electrical isolation is important to the success of cathodic protection except where the system being protected cannot be electrically isolated and the CP system is designed to take this into account. In an isolated system, the failure of the CP system to maintain a satisfactory level of cathodic protection might be caused by an electrical short to another metallic structure including other pipelines, power grounds, station grounding, etc.

Locating the Problem

There are many methods to locate an electrical isolating device and/or tests to determine if the device is functioning properly:

- Pipeline/cable locators
- Isolation testing instrument

- Structure-to-electrolyte potential
- Interrupted structure-to-electrolyte potential
- DC line current measurements
- Fixed cell to moving ground
- Current response test
- Isolation resistance test.

Each technique has advantages and disadvantages including whether or not the particular test can be used under the circumstances and if the test is conclusive under those circumstances.

Use of a Pipeline/Cable Locator for Isolation Testing

A pipeline or cable locator can be used to locate the pipe as well as locate electrical short circuits or discontinuities on a structure. The AC signal is placed onto the structure using either a conductive or an inductive locator. The signal placed onto the structure will stay only on the structure unless there is an electrical contact with a foreign structure. If the AC signal is not detected on the foreign structure or portion of the structure meant to be electrically isolated, then the two are electrically isolated.

If the signal continues past the electrical isolating device, then the isolating device is not functioning and the two metallic structures are electrically continuous.

Most locators include a transmitter and receiver. The transmitter is a source of AC radio frequency that is used to impress a signal on the structure. The receiver picks up the signal on the structure and provides it to the user as an amplifier sound and/or visual signal. The sound of the signal, such as the frequency and rate of the pulse, can be controlled by the transmitter.

There are two types of pipe locators—conductive and inductive. Some locators contain both types in one unit. The conductive pipe locator is of most use in locating shorts.

Conductive Pipe Location

The conductive locator uses a radio frequency AC signal and is electrically connected to the structure under investigation by a direct wire.

The transmitter converts DC from dry cell batteries to AC by means of a vibrator circuit. This AC can then be passed through a transformer to give an output of several hundred volts, peak. This AC signal is connected between ground and the structure to be traced.

When the receiver is near the structure, the AC field around the structure induces a voltage in the pickup coil. This voltage is amplified and produced as an audible signal heard by the user. Figure 6.47 illustrates the principle of the conductive locator.

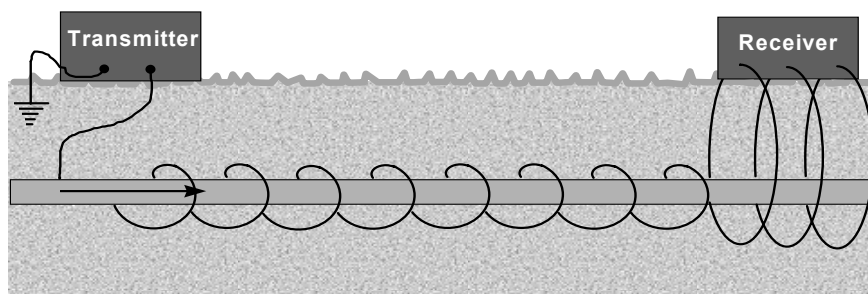


Figure 6.47 Conductive Pipe Locator Principle

Inductive Pipe Location

An inductive locator uses a radio frequency AC signal, which is induced in the structure to be located by an induction coil that is part of the transmitter.

Inductive-type locators permit the location of underground metallic structures where it is not feasible to attach directly to the structure, as in the case of the conductive locator. This is accomplished by a coil in the transmitter that establishes a strong magnetic field that induces an AC current in the structure. The AC field surrounding the structure can then be detected in a manner similar to that described for the conductive locator. Figure 6.48 illustrates the principle of the inductive locator. Signals can be induced on both sides of an isolation giving a false indication of a short.

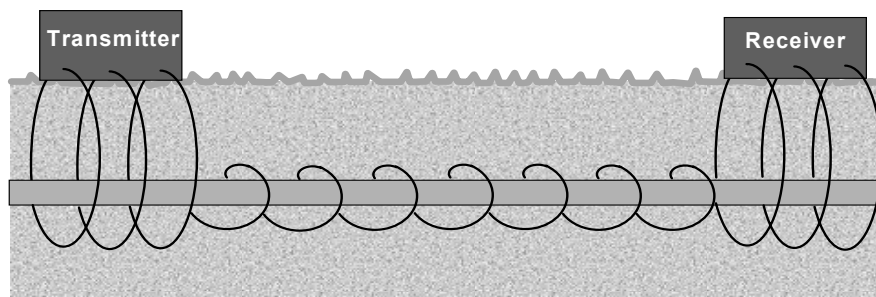


Figure 6.48 Inductive Pipe Locator Principle

Testing Above Grade Isolating Flange/Unions

An “isolation checker” is an instrument specifically built to check both below grade as well as abovegrade isolation devices (see Figure 6.49). For abovegrade isolation devices, the isolation checker probes are placed in contact with each side of the flange or union. A functioning electrical isolation device will show a full-scale deflection while an electrically shorted device will show a deflection toward zero on the scale.



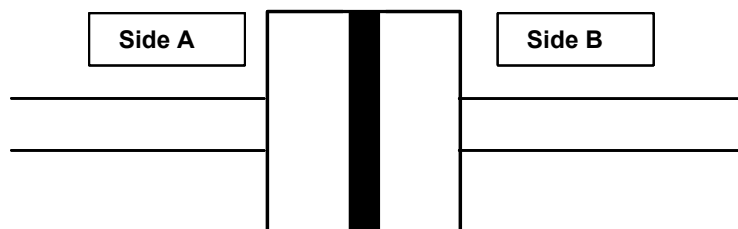
Figure 6.49 Isolation Checker

If the electrical isolating device is buried and test wires exist on both sides of it, an underground “isolation checker” may be used. This instrument is similar to the above grade isolation checker but is designed to be used only with an underground isolating fitting. It can be used to test for a shorted isolating bolt or stud if it has double isolating washers.

Structure-to-Electrolyte Potential for Isolation Testing

One can test the effectiveness of an isolating fitting using structure-to-electrolyte potentials. Placing the reference electrode in one location and not moving the electrode, a structure potential can be measured from each side of the fitting. If the structure potentials are identical or nearly identical, the possibility exists that the isolating fitting is shorted. If there is an appreciable difference in structure potentials from one side of the fitting to the other, the two sides of the fitting are electrically isolated.

Example



Flange Side	Isolated	Shorted
A	$-1.560 \text{ V}_{\text{CSE}}$	$-0.875 \text{ V}_{\text{CSE}}$
B	$-0.950 \text{ V}_{\text{CSE}}$	$-0.874 \text{ V}_{\text{CSE}}$

Interrupted Structure-to-Electrolyte Potential to Test Isolation

Using a current interrupter installed in the nearest CP current source, the protective current can be cycled ON and OFF. Measuring an ON and OFF structure to electrolyte potential on each side of the isolating device can determine if the device is functioning or not. With a functioning electrical isolating device, the side with the current source that is interrupted will have a more negative ON potential than the OFF potential and the two values will be cycling on the same timing as the current interrupter. On the opposite side of the isolating device, the ON and OFF potentials will be nearly the same and sometimes, the OFF potential will be more negative than the ON potential.

If the isolating device is not functioning properly, the ON and OFF potentials will be the same on each side of the isolating device and the potentials on both sides will be swinging with the same timing cycle as the current interrupter.

Example

Flange Side	Isolated		Shorted	
	ON	OFF	ON	OFF
A	$-1.560 V_{cse}$	$-0.950 V_{cse}$	$-0.875 V_{cse}$	$-0.750 V_{cse}$
B	$-0.950 V_{cse}$	$-0.948 V_{cse}$	$-0.875 V_{cse}$	$-0.750 V_{cse}$

DC Line Current to Test Isolation

Measuring DC pipeline currents can help locate an electrical short and help determine if an isolating device is functioning properly. These tests can be run many ways. First, two electrical connection points to the pipeline that are separated by at least several hundred feet must exist. These can be two test stations, an IR-drop (calibrated) test station, two valves, or two probe bars. Figure 6.50 illustrates the principle behind this test which is discussed in more detail later in this chapter. In addition, examples are given for calculating the pipe resistance and current magnitude.

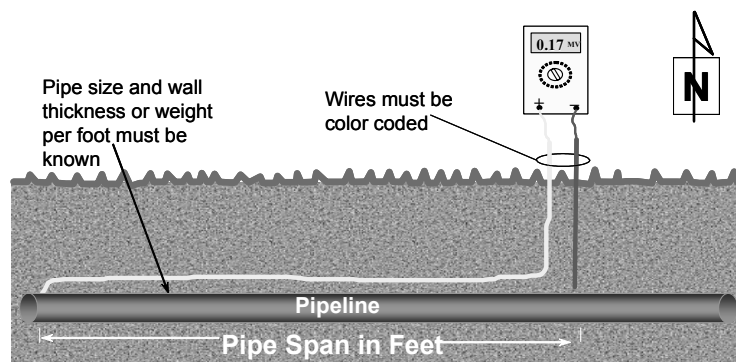


Figure 6.50 Two-Wire Line Current Test

By measuring the magnitude and direction of current flow in the pipeline steel, one can trace the direction the current is taking to return to its source (Figure 6.51). If current is flowing towards an electrical isolating device and there are no current sources or interference bonds located between where you are measuring the current and the isolating device, then the device is not functioning properly and is shorted.

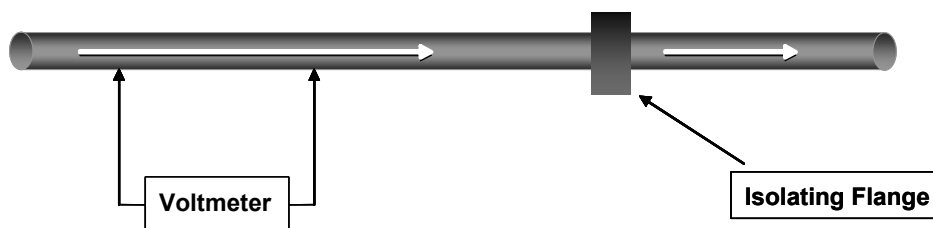


Figure 6.51 Shorted Isolating Buried Flange

Fixed Cell to Moving Ground for Continuity Test

In this test, a reference electrode is connected to one lead from a multimeter and placed at a fixed location while the second lead from the multimeter is placed in contact with various parts of the structure. If essentially the same structure-to-electrolyte potential is read from each point of electrical contact, continuity is indicated (Figure 6.52). It is possible that an isolated portion of the structure could have the same potential as the rest of the structure. If you suspect this is the case then other tests outlined in this chapter should be completed.

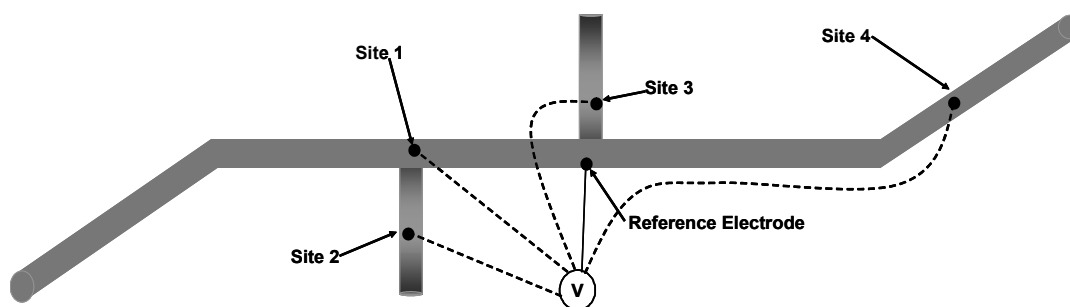


Figure 6.52 Fixed Cell to Moving Ground Technique

Example

Site No.	Electrically Continuous	Electrically Discontinuous
1	-1.560 V _{CSE}	-1.560 V _{CSE}
2	-1.560 V _{CSE}	-1.456 V _{CSE}
3	-1.560 V _{CSE}	-1.652 V _{CSE}
4	-1.560 V _{CSE}	-1.488 V _{CSE}

Current Response

Applying a temporary current to one side of an electrical isolation device can determine if the device is functioning properly. Using the setup illustrated in Figure 6.53 below, the side of the isolating device which has the temporary current applied to it will become more negative with the application of current

while the pipe on the opposite side will remain the same. If the electrical isolating device is not functioning properly, the shift in potential will be the same on both sides of the isolating device.

In addition, cycling the temporary current using a current interrupter will confirm electrical isolation in the same manner as previously stated. If the two structures are isolated, the far side of the isolating device will not have “cycling” potentials.

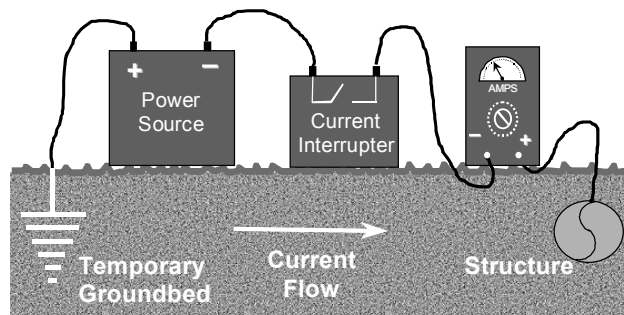


Figure 6.53 Current Response

Example

Flange Side	Electrically Isolated		Electrically Shorted	
	ON	OFF	ON	OFF
A*	$-1.650 \text{ V}_{\text{CSE}}$	$1.345 \text{ V}_{\text{CSE}}$	$-1.650 \text{ V}_{\text{CSE}}$	$1.345 \text{ V}_{\text{CSE}}$
B	$-1.300 \text{ V}_{\text{CSE}}$	$1.300 \text{ V}_{\text{CSE}}$	$-1.650 \text{ V}_{\text{CSE}}$	$1.345 \text{ V}_{\text{CSE}}$

* Flange side with temporary current applied cycling ON and OFF.

Casings

A casing may experience either a “metallic short” or an “electrolytic couple.” A metallic short is a metal-to-metal contact between the casing and the carrier pipe. Such a short will usually cause an electropositive attenuation in the pipe-to-electrolyte potential in the area of the casing. The potential might attenuate, for example from $-950 \text{ mV}_{\text{CSE}}$ to $-750 \text{ mV}_{\text{CSE}}$. The electropositive attenuation is especially pronounced if the casing is bare. Discovery of such a change in the usual pipe-to-electrolyte potential should lead you to suspect a shorted casing. If a metallic short exists, the structure potentials to a copper-copper sulfate electrode will be essentially the same from the pipe and the casing test wires.

An electrolytic couple occurs when a low-resistance electrolyte such as water or mud gets into the annular space between the casing and the carrier pipe, the pipe-to-electrolyte potential of the casing may shift with the application of current. If the casing is isolated the shift on the casing will not be as great as that of the pipeline and there will still be a potential difference between the pipe and the casing.

Indication of Problems

A casing which is shorted to the carrier pipe is typically detected when one or all of these circumstances occur:

- Low structure-to-electrolyte potential profile in vicinity of a casing
- Sudden overall deterioration of cathodic protection levels
- Annual test station survey reveals the pipeline and casing have nearly the same structure-to-electrolyte potentials.

Locating the Problem

The following are methods used to detect casings shorted to carrier pipes.

1. Structure-to-Electrolyte Potential Survey

Place the reference electrode as close to the end of the casing as possible. Measure the pipe-to-electrolyte and casing-to-electrolyte potential as shown in Figure 6.54. The values should be significantly different if the carrier pipe is cathodically protected. If the difference between the two potentials is less than 100 mV, the casing might be shorted to the carrier pipe or, coincidentally, be at similar potentials and further testing is required.

Care should be taken as conclusions have been incorrectly drawn from structure potentials that were measured on test wires assumed to be casing wires when in reality they were attached to either a foreign structure or to the carrier pipe. Confirmation of test wires should take place and can include using the casing vents to check test wire continuity.

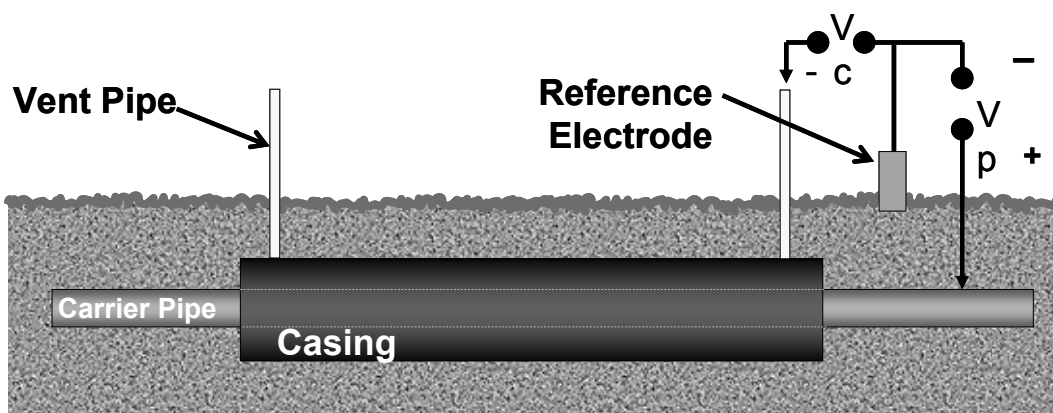


Figure 6.54 Set-Up for Measuring the Pipe-to-Electrolyte and Casing-to-Electrolyte Potential

Example

	Shorted	Isolated
C/S	$-0.900 V_{CSE}$	$-0.750 V_{CSE}$
P/S	$-0.900 V_{CSE}$	$-0.910 V_{CSE}$

2. Interrupted Structure-to-Electrolyte Potential Survey

Temporarily interrupting the nearest cathodic protection system will assist in testing casing/carrier pipe shorts and test wire continuity. With the nearest source interrupted, measure the ON and OFF structure-to-electrolyte potentials from both the casing and carrier pipes. If the casing potentials cycle in unison with the carrier pipe potentials and are shifting the same magnitude between the ON and OFF, then the casing and carrier pipe are likely electrically shorted. If the casing potentials are shifting in the opposite direction or are shifting only slightly between the ON and OFF, then the two structures likely are not shorted. Again, the reference electrode should be located near the end of the casing pipe and should not be moved during these sets of measurements.

Care should be taken during the interpretation of this data. If the CP current source is in close proximity to the casing, it is possible for the casing potentials to shift between the ON and OFF cycle as a result of being in the anodic gradient of the CP source.

Example

	Shorted		Isolated	
	ON	OFF	ON	OFF
C/S	$-1.56 V_{CSE}$	$-1.00 V_{CSE}$	$-1.00 V_{CSE}$	$-1.00 V_{CSE}$
P/S	$-1.56 V_{CSE}$	$-1.00 V_{CSE}$	$-1.56 V_{CSE}$	$-1.00 V_{CSE}$

3. Structure-to-Electrolyte Potential Change (Current Response Test)

Measure the structure-to-electrolyte potential and casing-to-electrolyte potential with respect to reference electrode placed on the soil directly above the structures. Use the vent, test wires on the casing, or a probe bar to contact the casing. Impress a current on one of the two structures using an interruptible DC power supply and a temporary anode bed (Figure 6.55). Measure E_{ON} and E_{OFF} structure-to-electrolyte potential readings on both structures. If the potentials of the two structures become more negative by the same magnitude and in the same direction when the current is on, they are shorted. If the potential of the structure that the temporary CP current is being impressed upon becomes more negative while the potential of the other structure decreases or stays the same, the two structures are electrically isolated.

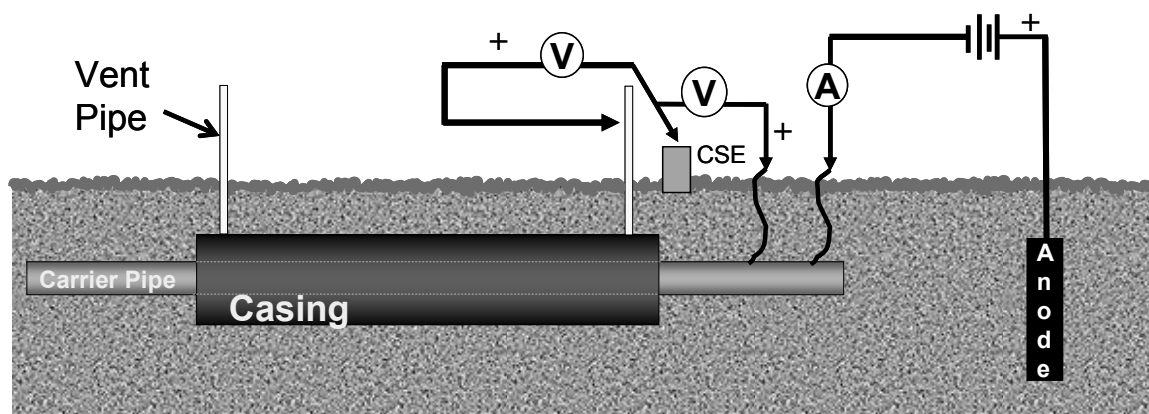


Figure 6.55 Illustration of Structure-to-Soil Potential Change Measurements

Example

	Shorted (ON/OFF)		Isolated (ON/OFF)	
	ON	OFF	ON	OFF
C/S	$-1.50 V_{CSE}$	$-1.25 V_{CSE}$	$-1.25 V_{CSE}$	$-1.25 V_{CSE}$
P/S	$-1.51 V_{CSE}$	$-1.25 V_{CSE}$	$-1.51 V_{CSE}$	$-1.25 V_{CSE}$

4. Resistance Between the Casing and Pipe

The resistance between the pipe and casing can be measured using an ammeter, voltmeter, and external DC power supply. Do not use a volt-ohmmeter due to the influence of the voltage between the structures. NACE Standard RP0200, “Steel-Cased Pipeline Practices”, describes the measurement technique.

5. Voltage or IR Drop Method

This method can be used to estimate the location of the electrical short between the carrier pipe and casing. The procedure calls for impressing a current between the casing and pipe from two different locations and measuring the resulting voltage drop. A ratio of the voltage drops compares to a ratio of the distance from the end to the contact. NACE Standard RP0200 describes the procedure and analysis.

6. Casing Depolarization Test

The casing is depolarized by showing a temporary current between it and a temporary electrode with the casing connected to the positive side of the current source. Potentials are measured on the pipe and casing at different amounts of current. The procedure is described in NACE Standard RP0200.

Soil Resistivity Testing**Purposes**

Soil resistivity is one factor that can determine the corrosivity of an environment. Resistivity is also essential in the design of cathodic protection systems.

Corrosivity Evaluations

Electrolyte resistivity and pH are two of the factors that determine the corrosivity of an electrolyte. Electrolyte resistivity is a measure of the ability of the electrolyte to support electrochemical corrosion, and electrolyte pH is a measure of the acidity or alkalinity of the electrolyte. Both influence the corrosion rates of metals placed underground or that are submerged.

Resistivity and pH are not the only factors affecting corrosion since total acidity, aeration, moisture content, soil type, soil permeability and composition, and heterogeneity play a role in determining the corrosivity of a given soil. Because of the natural heterogeneity of soil, there is no single value of soil resistivity that represents a particular site. Instead, for a given site a range of values are measured and calculations made to determine the “layer” resistivities.

Measurement Techniques

Various means of measuring electrolyte resistivities are used. These include the Wenner Four-Pin Method as described in ASTM Test Method G57, Collins Rod, and electromagnetic induction methods.

Wenner Four-Pin Method

The four-pin resistivity method developed by Wenner involves the use of 4 pins driven into the ground (Figure 6.56). Current is applied to the outer pins, and the voltage drop between the inner pins is measured. The resistivity is a function of the current, voltage drop, and spacing of the electrodes (which is equal to the depth of the test). The current is usually applied using an instrument that supplies alternating current; otherwise, polarization effects occur at the electrodes that can alter the reading. If a DC current is used, “instant” current and potential measurements must be taken. Stray earth currents can also affect the readings if these effects are not separated from the data.

Instruments can use current generated from batteries by a vibrator (e.g., Vibroground or Nilsson), or current generated by hand cranking (e.g., Meggar). The Nilsson uses a voltage of 12 V and a frequency of 97 Hz and the Vibroground uses a voltage of 100 V and 97 Hz. The LEM is an automated, microprocessor-controlled instrument and uses a range of frequencies (50 to 128 Hz) and 48/20 V.

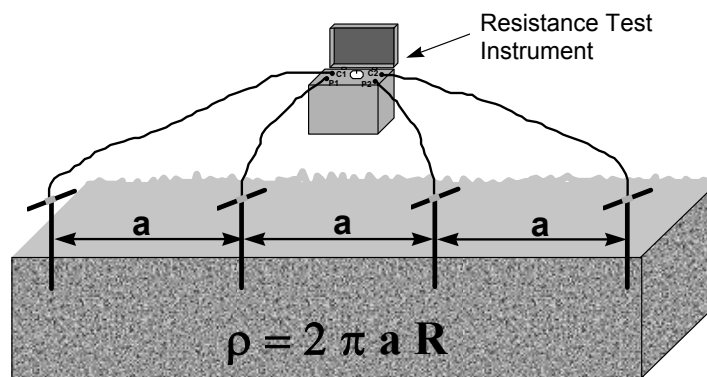


Figure 6.56 Wenner Four-Pin Soil Resistivity Measurement

The first step is to determine the resistance in Ω between the center pair of pins. Using the commercially available equipment detailed above, the resistance is indicated directly by the soil resistance meter. Resistivity is then calculated using the following formula:

$$\rho = 2\pi a R \quad \text{Eq. 6-22}$$

where:

- ρ = Resistivity, Ω -cm
- π = Constant Pi (3.1416)
- a = Spacing, cm
- R = Resistance, Ω

or, if spacing is measured in feet, with the resistivity still in Ω -cm, use the following formula:

$$\rho = 191.5 a R \quad \text{Eq. 6-23}$$

- ρ = Resistivity, Ω -cm
- a = Spacing, ft
- R = Resistance, Ω

For example,

If the resistance reading from the meter is 8 Ω at a pin spacing of 3.048 m (30.48 cm), then the average resistivity to an approximate depth of 3 m is

$$\rho = 2 \times \pi \times 304.8 \text{ cm} \times 8 \Omega = 15,320 \Omega\text{-cm}$$

or, similarly if the resistance reading is 8Ω at a pin spacing of 10 ft, then the average resistivity to a depth of 10 ft is

$$\rho = 191.5 \times 10 \text{ ft} \times 8 \Omega = 15,320 \Omega \cdot \text{cm}$$

If the line of soil pins runs closely parallel to a metallic structure, the presence of the structure may cause the indicated soil resistivity values to be lower than is actually the case. This is because a portion of the test current will flow along the metallic structure rather than through the earth. For this reason, this situation should be avoided. When taking soil resistivity measurements along a structure, it is good practice to place the line of pins perpendicular to the structure, with the nearest pin no closer than 15 ft from the structure.

Layer Resistivity Calculations

The resistance, R , at each given spacing (S), is the resistance from ground level to a depth equal to the spacing of the two inside pins. Figure 6.57 shows the average and layer resistivity.

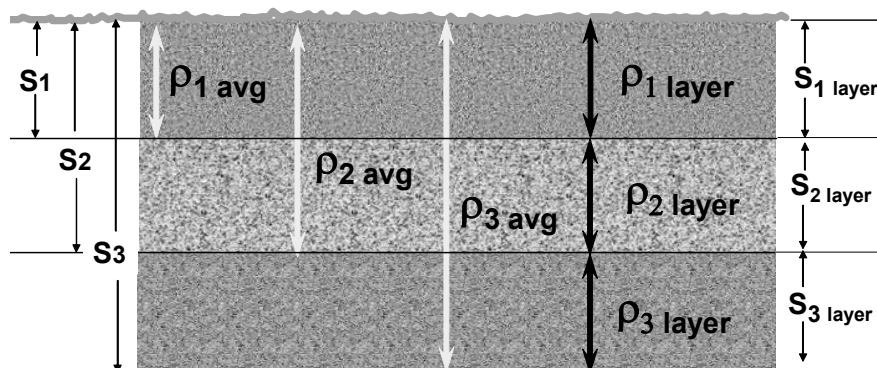


Figure 6.57 Average and Layer Resistivity

Using the Wenner Method, the soil resistivity, whether average or layer, is determined by Equations 6-24 or 6-25:

When calculating average resistivity, “ R ” is the resistance measured and “ a ” is the spacing of the pins. In determining layer resistivity, the resistance “ R ” for the layer can be calculated based on Barnes Layer Analysis which assumes the layers are in parallel and “ a ” is the thickness of the layer. Begin with the parallel resistance formula:

$$1 / R_T = 1 / R_1 + 1 / R_2 + 1 / R_3 + \dots + 1 / R_N \quad \text{Eq. 6-24}$$

If there are only two parallel resistances then:

$$R_2 = \frac{R_1 R_T}{(R_1 - R_T)} \quad \text{Eq. 6-25}$$

Therefore, based on the above illustration and equations, the following is true if the measured resistances are R_1 , R_2 , and R_3 with respect to spacings S_1 , S_2 , and S_3 .

$$\begin{aligned} \rho_{1 \text{ avg}} &= 2\pi S_1 R_1 \quad (191.5 S_1 R_1) \\ S_{1 \text{ layer}} &= S_1 \\ R_{1 \text{ layer}} &= R_1 \\ \rho_{1 \text{ layer}} &= 2\pi S_{1 \text{ layer}} R_{1 \text{ layer}} \quad (191.5 S_{1 \text{ layer}} R_{1 \text{ layer}}) \end{aligned}$$

$$\begin{aligned} \rho_{2 \text{ avg}} &= 2\pi S_2 R_2 \quad (191.5 S_2 R_2) \\ S_{2 \text{ layer}} &= S_2 - S_1 \\ R_{2 \text{ layer}} &= (R_1 R_2) / (R_1 - R_2) \\ \rho_{2 \text{ layer}} &= 2\pi S_{2 \text{ layer}} R_{2 \text{ layer}} \quad (191.5 S_{2 \text{ layer}} R_{2 \text{ layer}}) \end{aligned}$$

$$\begin{aligned} \rho_{3 \text{ avg}} &= 2\pi S_3 R_3 \quad (191.5 S_3 R_3) \\ S_{3 \text{ layer}} &= S_3 - S_2 \\ R_{3 \text{ layer}} &= (R_2 R_3) / (R_2 - R_3) \\ \rho_{3 \text{ layer}} &= 2\pi S_{3 \text{ layer}} R_{3 \text{ layer}} \quad (191.5 S_{3 \text{ layer}} R_{3 \text{ layer}}) \end{aligned}$$

The results of sample soil resistivity calculations shown below that may be derived from data acquired using the Wenner Method and the Barnes Layer calculations.

Table 6.3 Examples of Layer Resistivity Calculations

SPACING (ft) [cm]	RESISTANCE (Ω)	RESISTIVITY AVERAGE (Ω -cm)	LAYER RESISTANCE (Ω)	RESISTIVITY LAYER (Ω -cm)
5.22 [159.1]	10.0	10,000	10.0	10,000
10.44 [318.2]	7.4	14,795	28.5	28,452
15.66 [477.3]	3.1	9,295	5.33	5,328

The “Resistivity Average” data in Table 6.3 is calculated below.

$$\rho_{ave} = \frac{2 \pi a R}{\ln 4}$$

$$\begin{aligned}\rho_{ave 1} &= 2 \pi \times 159.1 \text{ cm} \times 10 \Omega \\ &= 10,000 \Omega\text{-cm}\end{aligned}$$

Or in feet

$$\begin{aligned}\rho_{ave 1} &= 191.5 \times 5.22 \text{ ft} \times 10 \Omega \\ &= 10,000 \Omega\text{-cm}\end{aligned}$$

$$\begin{aligned}\rho_{ave 2} &= 2 \pi \times 318.1 \text{ cm} \times 7.4 \Omega \\ &= 14,795 \Omega\text{-cm}\end{aligned}$$

Or in feet

$$\begin{aligned}\rho_{ave 2} &= 191.5 \times 10.44 \text{ ft} \times 7.4 \Omega \\ &= 14,795 \Omega\text{-cm}\end{aligned}$$

$$\begin{aligned}\rho_{ave 3} &= 2 \pi \times 477.3 \text{ cm} \times 3.1 \Omega \\ &= 9,295 \Omega\text{-cm}\end{aligned}$$

Or in feet

$$\begin{aligned}\rho_{ave 3} &= 191.5 \times 15.66 \text{ ft} \times 3.1 \Omega \\ &= 9,295 \Omega\text{-cm}\end{aligned}$$

The “Layer Resistance” and the “Resistivity Layer” data in Table 6.3 are calculated as follows:

$\rho_{1 \text{ layer}}$

$$\rho_{1 \text{ layer}} = \rho_{1ave} \text{ as they are the same layer of soil.}$$

$\rho_{2 \text{ layer}}$

$$\rho_{2 \text{ layer}} = 2\pi S_{2 \text{ layer}} R_{2 \text{ layer}} \text{ (with } S_{2 \text{ layer}} \text{ in cm)}$$

where

$$\begin{aligned}S_{2 \text{ layer}} &= S_2 - S_1 \\ &= 318.2 \text{ cm} - 159.1 \text{ cm} \\ &= 159.1 \text{ cm}\end{aligned}$$

$$\begin{aligned}\text{Or} \\ &= 10.44 \text{ ft} - 5.22 \text{ ft} \\ &= 5.22 \text{ ft}\end{aligned}$$

and

$$\begin{aligned}R_{2 \text{ layer}} &= (R_1 R_2) / (R_1 - R_2) \\ R_{2 \text{ layer}} &= (10.4 \Omega \times 7.4 \Omega) / (10.4 \Omega - 7.4 \Omega) \\ &= 25.65 \Omega\end{aligned}$$

$$\begin{aligned}\rho_{2 \text{ layer}} &= 2\pi S_{2 \text{ layer}} R_{2 \text{ layer}} \\ &= 2 \pi \times 159.1 \text{ cm} \times 25.65 \Omega \\ &= 25,641 \Omega\text{-cm}\end{aligned}$$

Or if in feet

$$\begin{aligned}\rho_{2 \text{ layer}} &= 191.5 S_{2 \text{ layer}} R_{2 \text{ layer}} \\ &= 191.5 \times 5.22 \text{ ft} \times 25.65 \Omega \\ &= 25,641 \Omega\text{-cm}\end{aligned}$$

$\rho_{3 \text{ layer}}$

$$\rho_{3 \text{ layer}} = 2\pi S_{3 \text{ layer}} R_{3 \text{ layer}} \text{ (with } S_{3 \text{ layer}} \text{ in cm)}$$

where

$$\begin{aligned} S_{3 \text{ layer}} &= S_3 - S_2 \\ &= 477.3 \text{ cm} - 318.2 \text{ cm} \\ &= 159.1 \text{ cm} \end{aligned}$$

Or in feet

$$\begin{aligned} &= 15.66 \text{ ft} - 10.44 \text{ ft} \\ &= 5.22 \text{ ft} \end{aligned}$$

and

$$\begin{aligned} R_{3 \text{ layer}} &= (R_2 R_3) / (R_2 - R_3) \\ &= (7.4 \, \Omega \times 3.1 \, \Omega) / (7.4 \, \Omega - 3.1 \, \Omega) \\ &= 5.33 \, \Omega \end{aligned}$$

$$\begin{aligned} \rho_{3 \text{ layer}} &= 2\pi S_{3 \text{ layer}} R_{3 \text{ layer}} \\ &= 2\pi \times 159.1 \text{ cm} \times 5.33 \, \Omega \\ &= 5328 \, \Omega\text{-cm} \end{aligned}$$

Or if depth in feet

$$\begin{aligned} \rho_{3 \text{ layer}} &= 191.5 S_{3 \text{ layer}} R_{3 \text{ layer}} \text{ (with } S_{3 \text{ layer}} \text{ in ft)} \\ &= 191.5 \times 5.22 \text{ ft} \times 5.33 \, \Omega \\ &= 5,328 \, \Omega\text{-cm} \end{aligned}$$

Single Rod Method

Another instrument mounts the electrodes on a single rod. An alternating current is supplied, and the resistivity is measured using a galvanometer (e.g., Collins Rod). These techniques measure local volumes of soil, making them useful for that very reason. They fit into confined spaces, such as next to tanks and between pipes, where the standard Wenner Four Pin method would not provide accurate results.

The probe-type device consists of a metal probe rod, which can be pushed into the ground to the desired depth. Typically, the tip of the rod is isolated from the remainder of the rod so that the resistance between the rod tip and rod body can be measured. The resistance measured is a function of the soil resistivity. This permits calibrating the resistance measuring device directly in Ω -cm or measuring the resistance and multiplying the observed value by some factor to obtain a value of soil resistivity. Figure 6.58 shows this device.

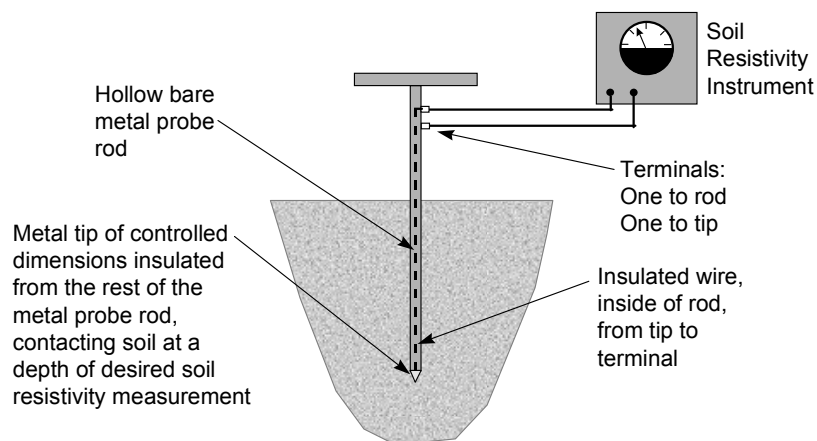


Figure 6.58 Probe Type Resistivity Meter

Soil/Electrolyte Box

Another method of measuring resistivity does not rely on contact with the ground at all.

Soil or electrolyte box measurements of resistivity involve placing water or a soil sample in a container having electrodes. These electrodes are then connected to a power supply and a voltage measuring device, and the resistance of the soil between two potential electrodes is measured. There are two different methods of preparing the soil for testing using this measurement technique. ASTM G51 provides a method for testing the soil in the as-received state and saturated with ground water, distilled water, or tap water. AASHTO T288 calls for drying the sample, sieving it, and then adding water. The measurement is made in a specially designed box having two electrodes. All of these methods measure a “minimum” resistivity of a relatively small soil sample that may not represent the in-situ soil in terms of compaction, pressure, temperature, permeability, or

moisture content. These test methods should not, therefore, be expected to replicate field measurements.

A soil/electrolyte box, shown in Figure 6.59, can be made or a commercial model purchased. The commercial models are usually a clear, plastic box constructed with end plates for current input and pins through the side for potential measurements.

The formula for resistivity is:

$$\rho = \frac{R \times A}{L} \quad \text{Eq. 6-26}$$

If a soil box is constructed such that the cross-sectional area and the length are equal, then the calculated value of resistivity would equal the measured resistance. That is,

If $L = A$

then

$\rho = R$

but

ρ = soil resistivity (Ω -cm)

R = resistance from test (Ω).

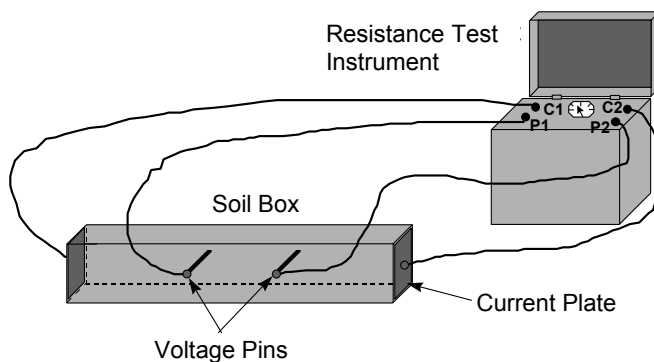


Figure 6.59 Soil Box Resistivity Test

Some commercially available soil boxes are sized for this straight one-to-one conversion but remember the units for resistance (Ω) and resistivity ($\Omega\text{-cm}$) are different. Without the correct units the result is incorrect.

Measuring pH

Electrolyte pH can be measured in several ways. For liquids, pH (litmus) paper or a pH meter may be used. For soils, a pH meter may be used, or a filtrate may be made from distilled water and a soil sample and the pH measured with litmus paper, a pH meter, or a pH test kit. Note that a pH meter uses a glass electrode with a rather fragile glass bulb on the bottom. Care must be taken when using these instruments not to break the electrode bulb.

Soil pH may also be measured using an antimony electrode and a copper-copper sulfate electrode. The antimony electrode consists of a slug of antimony metal in the bottom of a nonmetallic tube. The slug is connected to a terminal on the top of the tube.

It is important to keep the antimony shiny and bright. Use fine non-metal bearing sand paper or emery cloth for cleaning. Do not use steel wool or other metallic abrasive since particles of metal may become embedded in the antimony and affect the reading.

The antimony electrode and copper-sulfate reference electrode are placed close together with the electrode tips in the soil and connected to a voltmeter. It does not matter which cell is connected to which terminal of the meter since it is the potential between the two electrodes that is of interest. Take care not to get any copper sulfate on the antimony slug. There is a scale on the side of the antimony electrode that is calibrated in mV and pH. Once the potential difference between the two electrodes is obtained, the pH can be determined from the scale.

Concrete Structures

The following discussion pertains primarily to atmospherically exposed reinforced concrete structures, such as bridges and buildings. Reinforced concrete structures requiring cathodic protection are found in immersed situations as well, such as prestressed concrete pipes, prestressed concrete pilings, and cement-mortar-coated steel pipes.

Since cathodic protection requires a continuous structure, and since reinforcing is usually only connected through tie wires, electrical continuity must be verified. Items such as drains, railings, and expansion joints must also be continuous with reinforcing to avoid interference. Electrical continuity can be evaluated using AC-resistance measurements. Connections to two widely spaced points on the structure are made through the AC instrument. A resistance of less than $0.100\ \Omega$ indicates continuity.

Continuity can also be estimated by measuring the rebar-to-reference cell potential between several locations using a constant reference cell location. Rebar-to-structure potentials within $\pm 0.001\ \text{V}$ of each other suggest that the points are continuous. Measurements greater than $\pm 0.001\ \text{V}$ but less than $\pm 0.003\ \text{V}$ indicate uncertain continuity, and measurements greater than $\pm 0.003\ \text{V}$ indicate that the structure is discontinuous.

Depth of concrete cover is important when an impressed current cathodic protection system is to be installed. The anode must not come into contact with the rebar or any other metallic component of the structure, otherwise a short circuit will occur rendering the system useless. Depth of cover is measured using a Pachometer.

Metal reinforcing-to-reference electrode potentials are taken on concrete structures to determine the probability of corrosion of the embedded metal. Details of this procedure are provided in ASTM Test Method C876, "Test Method for Half-Cell Potentials of Uncoated Reinforcing Steel in Concrete."

A high-impedance voltmeter is connected between the reinforcing steel and a reference electrode placed on the surface of the concrete. The most commonly used reference electrode is the copper-copper sulfate half-cell. Excavation of the concrete to expose the reinforcing steel might be required to obtain the structure contact. Because of the high resistance inherent in the measurement circuit, the voltmeter must have sufficient input impedance to accurately measure the half-cell potentials. The minimum voltmeter impedance should be $10 \times 10^6\ \Omega$ and be selectable to higher values in order to identify significant resistances in the circuit.

To reduce the contact resistance between the concrete surface and the half-cell, a moist sponge is placed between the half-cell and the surface. It is also desirable

to pre-moisten the entire surface with clean potable water. This will reduce instabilities, but will result in a “leveling” of the measured potentials.

Half-cell potential measurements can be interpreted as follows:

Potential	Probability of Corrosion
More positive than –200 mV	< 5 percent
–200 to –350 mV	About 50 percent
More negative than –350 mV	> 95 percent

Potential measurements on concrete that is completely saturated, e.g., submerged piling, may be more negative than –350 mV yet have little corrosion activity because the water saturation limits oxygen diffusion which reduces corrosion.

Potential measurements are usually taken in a grid pattern, for example, one reading every 2 to 5 ft (0.6 to 1.5 m). The resulting data is plotted on a contour map showing areas that are corroding.

Direct Inspection

Direct inspection involves physical inspection of the structure itself. The surface of the structure must be exposed; it is then cleaned and examined for corrosion. Measurements of general corrosion and pitting can be made and compared to previous data. There should be no new or future corrosion if the cathodic protection system is working.

Leak Frequency

Comparing the cumulative frequency of leaks vs. time often identifies the effect of corrosion. It is typical of corrosion that the cumulative frequency increases logarithmically with time. Leaks that occur from purely mechanical causes would not behave with such regularity. The effect of cathodic protection is to slow down or flatten the leak rate curve.

Figure 6.60 is an example of a leak vs. time curve before and after the application of cathodic protection. Figure 6.60 comes from actual data on the leak history of a cast iron water main before and after cathodic protection was installed. The leaks occurring before 1984 show the logarithmic increase in the

number of leaks with time. The leaks are shown to have essentially stopped after cathodic protection was installed.

Maintaining leak record curves is a method that can be used to prove the effectiveness of cathodic protection. It is particularly useful for owners of structures that are not regulated by a government agency.

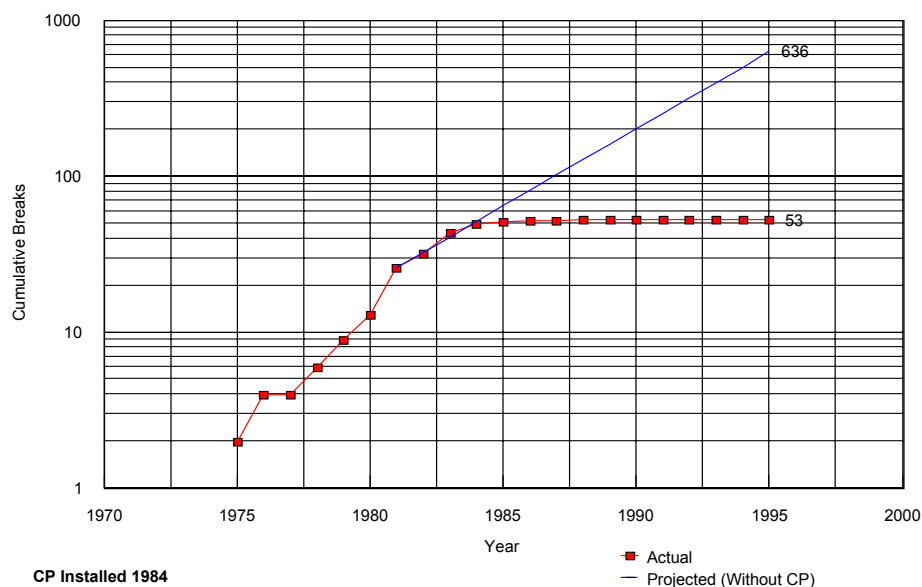


Figure 6.60 Cumulative Leaks vs. Time Before and After Cathodic Protection

In-Line Inspection

Instrumented or “smart” pigs using ultrasonic, eddy current, or mechanical measuring instrumentation can be used to measure corrosion from the inside of a pipe. Instrumented pigs contain sensing devices that scan the pipe wall searching for defects. Ultrasonic devices work by measuring the time it takes a high-frequency sound wave to travel across the pipe thickness and back to the transducer. The instrument is calibrated to measure this time as thickness of the pipe wall. Magnetic or eddy-current devices work by sensing deviations in a magnetic flux field caused by corrosion pits or other defects that distort the flux field.

CHAPTER 7

Stray Current and CP Interference

Stray Current

Stray currents are currents through electrical paths other than the intended circuit. Stray current is not the galvanic corrosion current between anodes and cathodes on the same structure. Stray currents, or interference currents, can be classified as being either static or dynamic.

Stray current can refer to either alternating current or direct current. AC stray current is more of a safety hazard than a corrosion problem. The exception is that AC can cause significant corrosion of aluminum. DC stray current causes significant corrosion of most metals.

Stray current is especially damaging because large currents, often involving many amperes, might be involved. On the other hand, even small amounts of stray currents can be highly damaging if discharged over a small surface area. In some areas, particularly around older rail rapid-transit systems or in the vicinity of underground mine railroads, pipelines may carry hundreds of amperes of stray current. For every ampere discharged from a structure, a certain amount of metal is lost. Faraday's Law allows us to relate the corrosion lost to the amount of current discharged. For ferrous metals (cast iron, ductile iron, steel), copper, and lead the loss rates are:

Ferrous	9.1 Kg / A-yr	(20 pounds / A-yr)
Copper	10.4 Kg / A-yr	(23 pounds / A-yr)
Lead	33.9 Kg / A-yr	(75 pounds / A-yr)

It is apparent that, if not controlled, stray current can destroy a structure very rapidly or at least to a potentially catastrophic situation. Structures in environments that normally would not be considered extremely corrosive will be subjected to accelerated corrosion when exposed to stray current conditions. Further consideration must be given to the current density for total penetration of the metal.

Stray current, being from an external source, enters the pipe or other structure through the soil (or other electrolyte) but does not cause corrosion at that point. Some amphoteric metals such as aluminum and lead may suffer “cathodic corrosion” in stray current “pick up” areas. Many structures, in fact, receive “free” cathodic protection from stray currents at the point of entry. The damaging effect of stray current typically occurs if the current *leaves* the structure through the electrolyte where corrosion will be accelerated.

The objective of stray current analysis is to determine:

- The source of the stray current.
- Where and over what area does the stray current enter the structure?
- Where and over what area does the stray current leave the structure?
- What is the magnitude of the stray current?
- How can the stray current be mitigated?

Dynamic Currents

Dynamic stray currents are those currents that vary in amplitude and/or change in the direction of current flow. These currents can be manmade or natural in origin.

Sources of Dynamic Stray Currents

Dynamic stray current can originate from any of the following sources:

- Transit systems
- Mining
- DC welding machines
- Electric power transmission
- Industrial plants (aluminum and chlorine production facilities)
- Telluric current

Examples of manmade sources are DC welding equipment, mining operations, and DC electrical railway systems. Telluric currents are naturally occurring stray currents that are caused by disturbances in the Earth's magnetic field by sun spot activity. Figure 7.1 shows stray currents from a DC railway. These are commonly called *stray traction currents*.

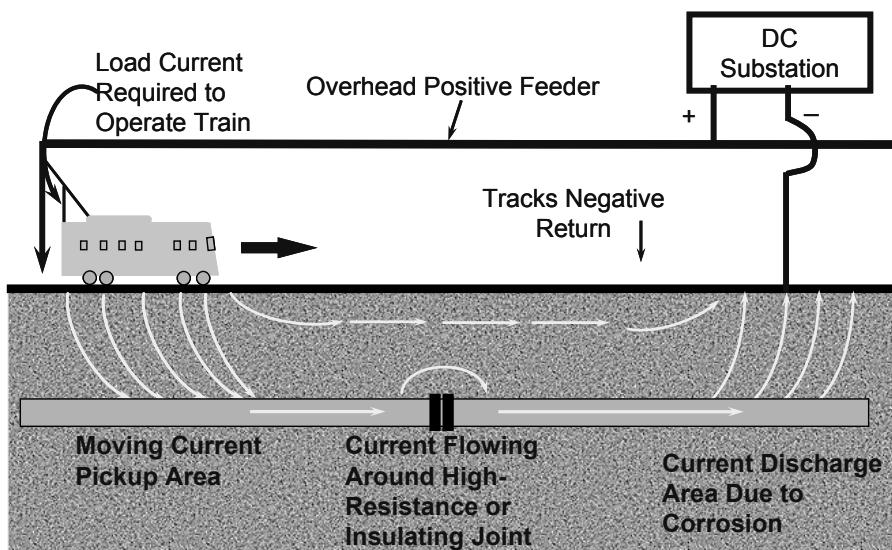


Figure 7.1 Illustration of Dynamic Stray Currents from a Transit System

Natural (Telluric) Currents

Telluric current is generated by the interaction of the solar wind (high-energy particles given off by the sun), the Earth's magnetic field, and metal structures at the surface of the Earth. The current generated shifts in magnitude and direction with time. It generally occurs during times of increased sun spot activity. Telluric currents create significant monitoring difficulties but have not been conclusively demonstrated to cause corrosion.

Detecting Dynamic Stray Currents

Dynamic stray currents can be readily detected from structure-to-electrolyte potentials and/or line current measurements. Dynamic stray currents can be indicated by a structure-to-electrolyte potential that is changing with time with the reference electrode in a stationary position in contact with the electrolyte. These potential changes are a direct result of current changes at the source of the interference.

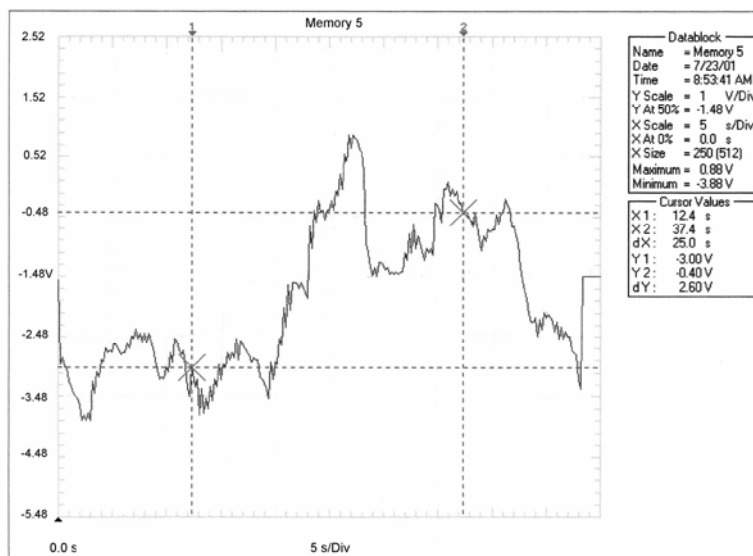


Figure 7.2 Pipe Potential Fluctuating Due to Dynamic Stray Current

Varying voltage gradients in the earth can be detected using two reference electrodes spaced ten to twenty-five feet apart. Reference electrodes placed on the soil over the existing pipeline or proposed pipeline route will show the voltage gradients that the pipe is (or will be) exposed to between the two cells.

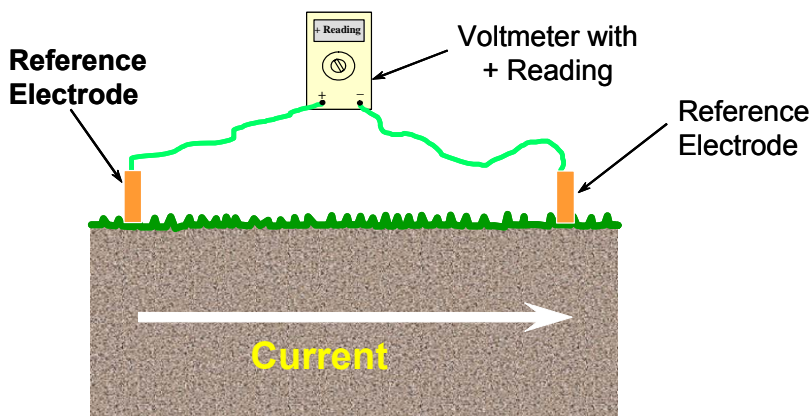


Figure 7.3 Potential Measurement Between Two Electrodes

The analysis of dynamic stray currents may require the use of correlations, or comparisons, of currents or voltages from one point on the structure to another. It is necessary to have sufficient test facilities on the structure to measure structure-to-soil potentials and current on the structure. If the structure has few or no test facilities and stray currents are detected, then install additional test facilities to permit a meaningful analysis.

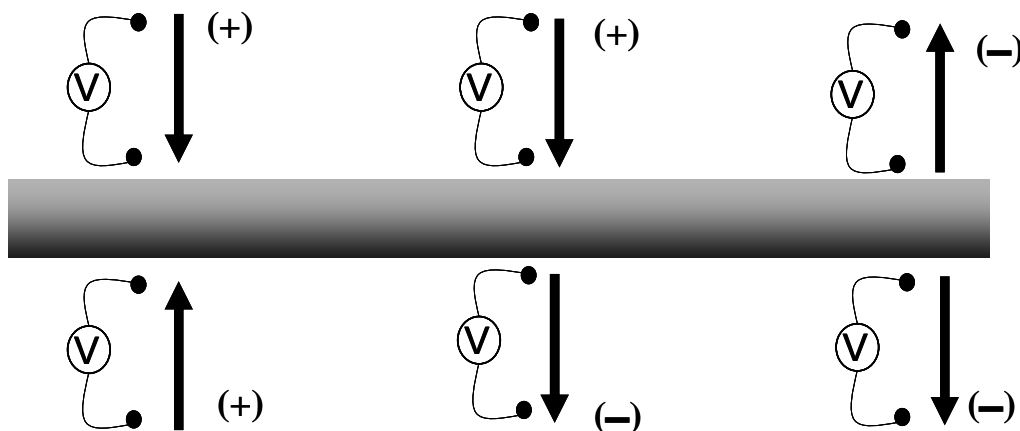


Figure 7.4 Potential Measurement Between Two Electrodes

Continuous Data Recording

The above analysis provides valuable information about where stray current enters and discharges from a structure. But it does not provide information on the value of the maximum stray current affecting the structure, does not show whether the stray current voltages observed during the test period are significant, and does not document the predominant *direction* of voltage or current. To perform this function, data about the stray current magnitude over time is needed. This data is obtained using a long term (24 hours or more) voltage or current recording. A strip chart recorder or data logger can be used for this purpose.

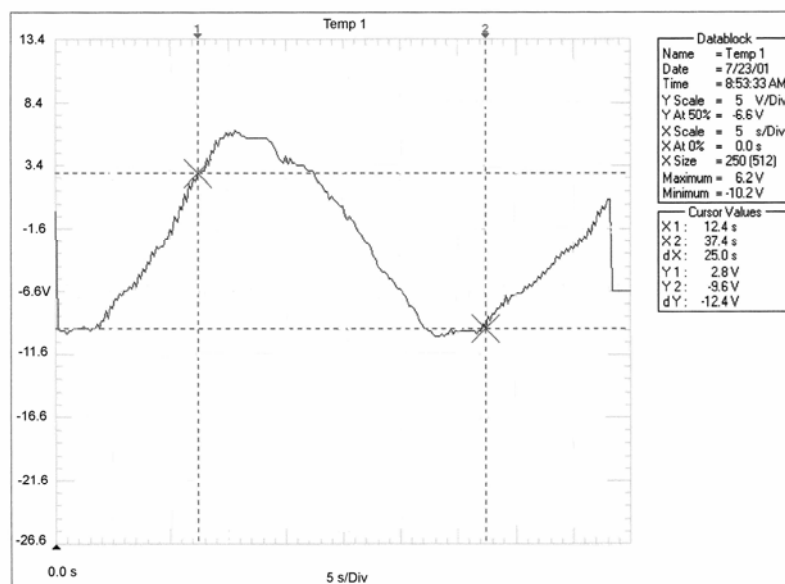


Figure 7.5 Data Logger Plot Illustrating Dynamic Stray Currents

Select the location to be tested using the results of the correlations, the best location being the one of most importance. The location of the recording should obviously be one of the test points used in the correlations as long as the voltages in the long term recording can be correlated back to the other test points using the correlations. However, almost any location will do. Select a location where the recording device will be safe and out of the way of traffic, pedestrians, and vandals. Note: The recording device should be identified with the company name, address, and telephone number.

More than one recording device might be needed.

Finding the Source of the Stray Current

Engineering solutions to stray current problems can be complex. Frequently, more than one source of current is involved. Transit systems, which are often the culprit, do not operate from a single substation; rather they are supplied by a number of substations operating in parallel and feeding many different lines simultaneously. Such transit systems operate with many thousands of amperes of current, and the effects can be seen for many miles on underground structures. If stray current is to be successfully drained from the structure of interest to the source, two conditions must be met.

The source must tend to pick up stray current at the point where the mitigation bond is to be installed. This is point determined using the correlations described above.

The structure must tend to discharge stray current at the point where the mitigation bond is to be installed. This point is also determined using the correlations described above.

Sufficient current must be drained to clear (mitigate) the most severe stray current exposure. This is determined by measuring or calculating the maximum current flow through the proposed bond or other mitigation system.

Static (Steady State) Currents

Static, or steady state, interference currents are defined as those that maintain constant amplitude and constant geographical paths. Examples include High-Voltage Direct Current (HVDC) ground electrodes and cathodic protection systems. Figure 7.6 shows how interference can occur from a cathodic protection system on a foreign pipeline.

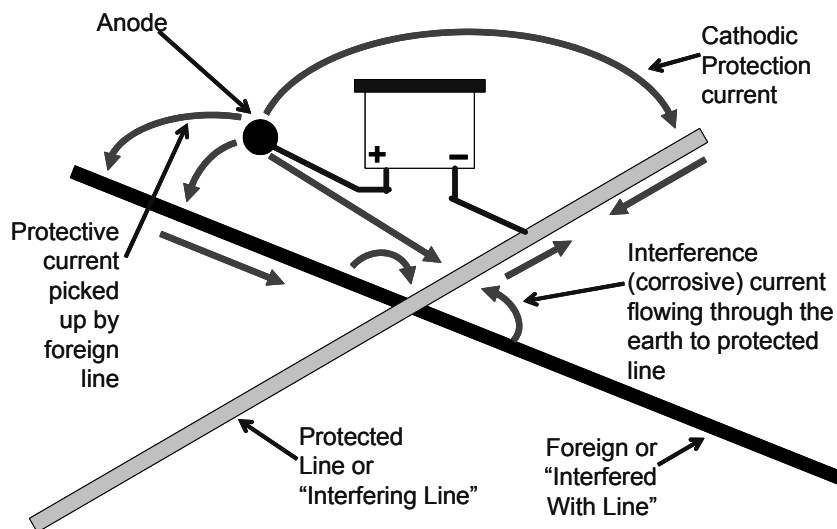


Figure 7.6 Static Stray Current Interference from a CP System

The polarity of the voltage gradients to remote earth affecting the foreign structure determines the type of interference. Interference can be either of the following two types or a combination of the two.

Cathodic Interference

When a voltage gradient overlaps a foreign structure and is negative with respect to remote earth, it promotes current discharge from the foreign structure in the area of influence. The cathodic gradient could be considered as

the controlling factor in this situation. If current discharges from a structure, then it must pick up current outside the area of influence. This is *cathodic interference* and is illustrated in Figure 7.7.

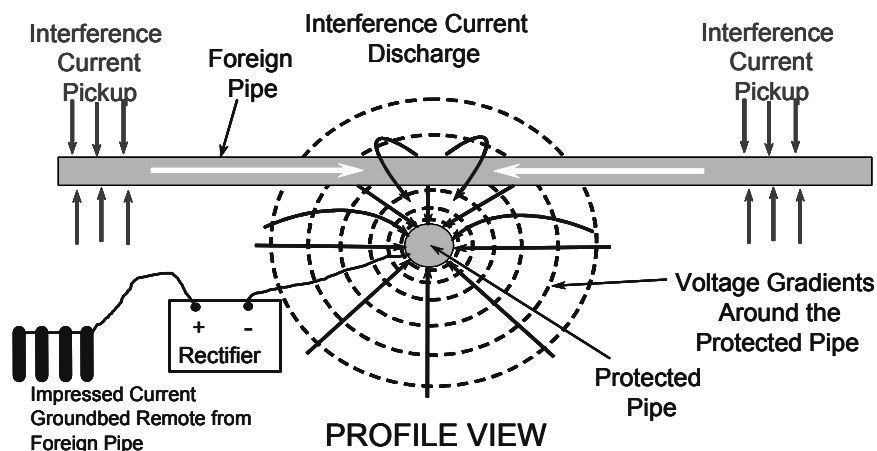


Figure 7.7 Cathodic Interference

Anodic Interference

Anodic interference is the opposite of cathodic interference. If a foreign structure crosses a voltage gradient that is positive with respect to remote earth, then it will promote current pickup on the foreign structure within the area of influence. The anodic gradient could be considered as the controlling factor in this case. Because current is picked up on the foreign structure, then current must discharge outside the area of influence. Anodic interference is illustrated in Figure 7.8.

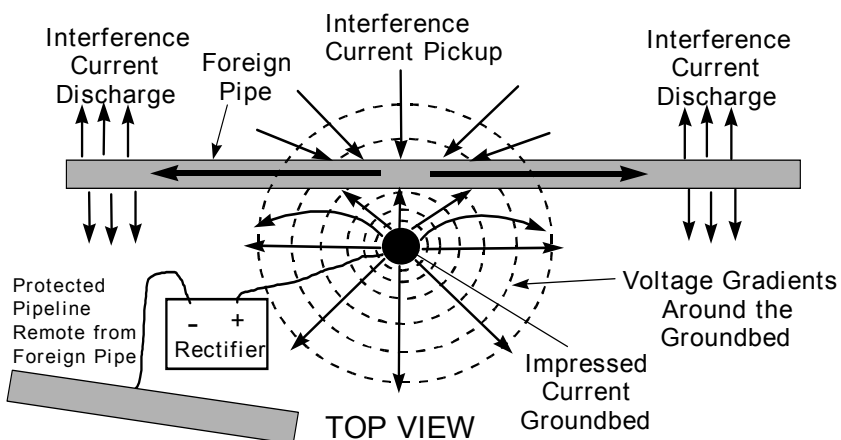


Figure 7.8 Anodic Interference

In certain conditions, a foreign structure may cross voltage gradients that promote anodic and cathodic interference from a single current source. For example, a foreign structure could cross the cathodically protected structure at one location and its impressed current grounded at another location.

Detection of Static Interference Currents

Certain changes and/or conditions in the system indicate the presence of interfering currents, including:

- Structure-to-electrolyte potential changes on the affected structure caused by the foreign cathodic protection current source
- Changes in line current magnitude or direction caused by the foreign cathodic protection current source
- Localized pitting in areas near or immediately adjacent to a foreign structure
- Breakdown of protective coatings in a localized area near a foreign anode bed or near any other source of stray direct current

Static interference is detected by analysis of structure-to-electrolyte potential surveys. The corrosion technician can sometimes misinterpret a structure-to-electrolyte potential survey because of static stray currents. In an unprotected pipeline, the corroding (anodic) areas exhibit a potential that is more negative when measured against a reference electrode, while the non-corroding (cathodic) areas yield a more positive (less negative) potential. Consider the case where stray current is flowing toward the pipe in a protective direction. In this case, the stray current makes the soil more positive than the pipe, and a more negative area appears on the structure-to-electrolyte potential profile, giving a false indication of a corroding area. The reverse is true in areas where stray current leaves the structure. Surface potential profiles may be misleading, as they represent a composite of current leaving the structure being surveyed and close to a crossing structure.

Static interference effects are detected similarly on protected pipelines. In this instance, however, the interpretation of the potentials is opposite to that described above for an unprotected pipeline. Figures 7.9 and 7.10 show examples of *close-interval surveys* (CIS) and the effect of static stray current on pipe-to-soil potentials for coated and uncoated cathodically protected

structures. The key points to consider in detecting static interference effects on a pipeline are:

- Potential profiles show abnormal variation from previous surveys.
- Large negative values are noted remote from any cathodic protection system on the pipeline or are noted on unprotected piping.
- Unusual currents are measured along the pipeline.
- Low negative or positive potentials are present.
- Changes in the current output of a nearby cathodic protection system may cause changes in the structure-to-electrolyte potential of the pipeline.

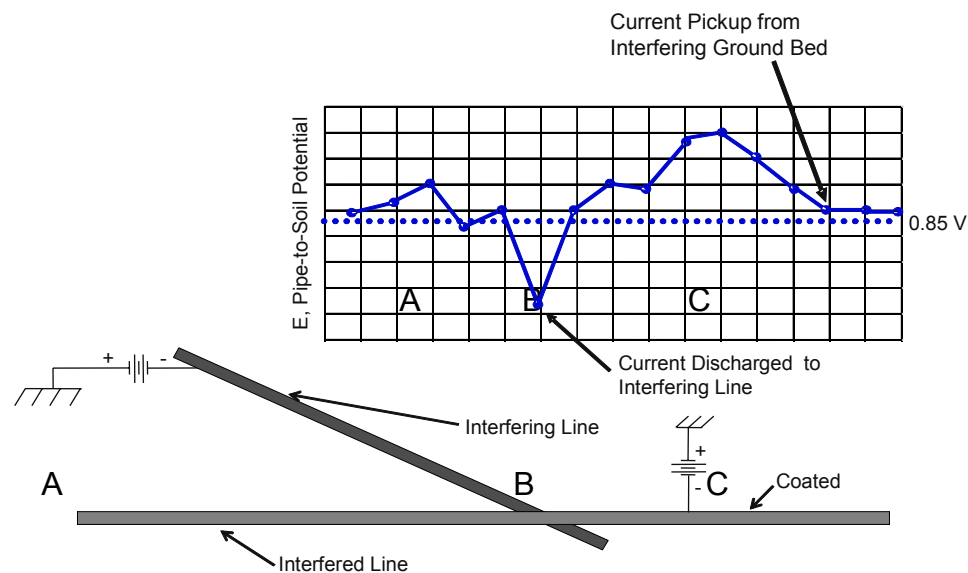


Figure 7.9 Effect of Static Stray Current on Pipe-to-Soil Potentials for Coated Cathodically Protected Structure

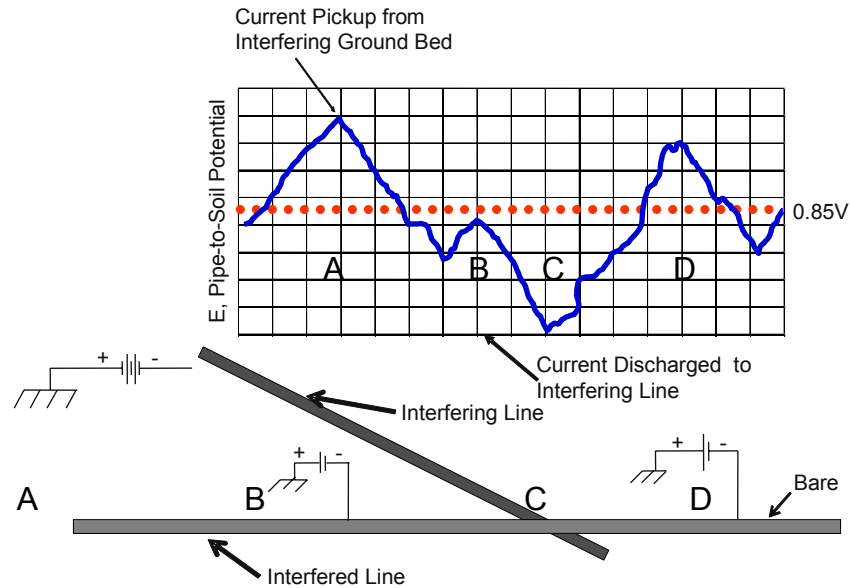


Figure 7.10 *Effect of Static Stray Current on Pipe-to-Soil Potentials for Uncoated Cathodically Protected Structure*

Sample Field Data

Structure-to-Electrolyte Potentials

When testing for stray current interference with an interrupter installed in the suspected source of interference it is critical that the ON and OFF structure-to-electrolyte potentials be identified by the length of the interrupter cycles and the assumption that the ON potential is the most negative value must NOT be made.

Examples of data are included in Table 7.1.

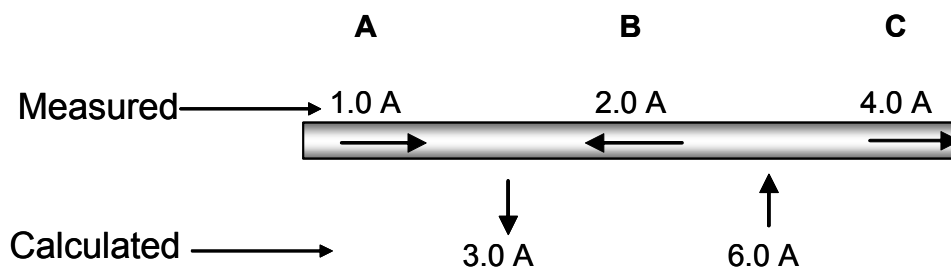
Table 7.1 Sample of Data Indicating Cathodic and Anodic Interference

Location	Structure-to-Electrolyte Potential (mV)				Remarks
	CP Structure		Foreign Structure		
	ON	OFF	ON	OFF	
X	-1100	-1600	-1300	-1000	Current pickup. Possible anodic interference on Foreign near CP anodes
Y	-1050	-1400	-650	-890	Current Discharge from Foreign. (Cathodic Interference)
Z	-1000	-1350	-900	-900	No curent pickup or discharge on Foreign

A more negative change in potentials as the current comes ON indicates a current pickup while a less negative change in potentials with the current coming ON indicates a current discharge. A continuous current pickup is occurring on the CP structure as expected. A current pickup is indicated at Point “X” on the foreign structure that suggests that it is in an anodic gradient possibly near the CP Structure’s anodes. A current discharge is indicated at Point “Y” on the foreign structure as the potentials become less negative as the CP structure’s CP system comes ON. The more negative potentials on the CP structure suggest that the foreign structure is in a cathodic gradient. There is no current pickup or discharge at Point “Z” on the foreign structure.

Current Measurements

Current measurements within a structure such as a pipeline can be used to predict current pickup and discharge areas using the principle of Kirchoff’s Current Law as illustrated by Figure 7.11.

**Figure 7.11 Current Pickup and Discharge Using Pipeline Current**

Current was measured at locations A, B, and C and the current discharge or pickup was determined using Kirchoff's Current Law, that is, the difference in current between the points measured represents a current pickup or discharge. In Figure 7.11, there must be a current discharge between A and B equal to the difference of current ($1.0 - (-2.0) = 3.0$ A) while there must be a current pickup between B and C equal to the current difference between these points ($-2.0 - 4.0 = -6.0$ A).

Resolving Interference Problems

Interference problems are individual in nature, and the resolution should be agreeable to all parties involved. Resolving interference problems generally involves one or more of the following:

- Removal of the detrimental effects of interfering current by installing a metallic return path
- Counteracting the effect of interfering current by applying cathodic protection
- Consultation with utility coordinating committee
- Removing or relocating the interfering current source
- Preventing the pick up or limitation of the flow of interfering current

These general approaches can be translated into some typical specific techniques:

- Adjust current output from the interfering systems.
- Reduce the stray current at the source (e.g., isolation from ground, better conductivity of the negative return paths, or lower voltages).
- Apply coating to strategic area(s).
- Install a mitigation bond, or electrical connection, between the structures to drain the stray current back to its source through an electrical conductor rather than the earth.
- Relocate existing structures or re-route proposed structures.
- Properly locate isolating fittings.

- Apply cathodic protection to the affected structure at the interfering current's discharge site.
- Relocate anodes
- Break up the structure of interest into smaller electrically isolated segments to reduce the stray current voltage gradients being traversed by the structure.

Installation of Metallic Bonds to Control Interference

Figure 7.12 illustrates a metallic bond between pipelines. The resistance of the bond must be lower than the parallel path through the soil.

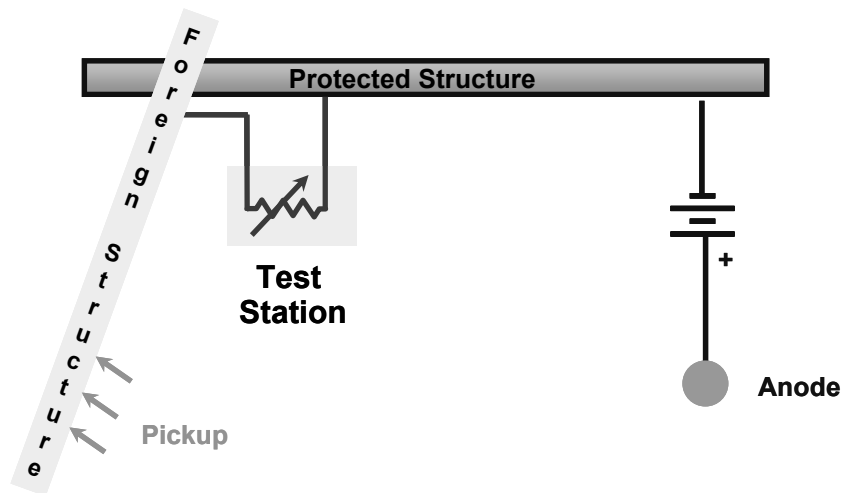


Figure 7.12 Electrical Bonding

Note: Protected structure must be more negative than foreign structure at the bond location to return current safely.

Figure 7.13 illustrates the use of a metallic bond to control stray current interference from a transit system.

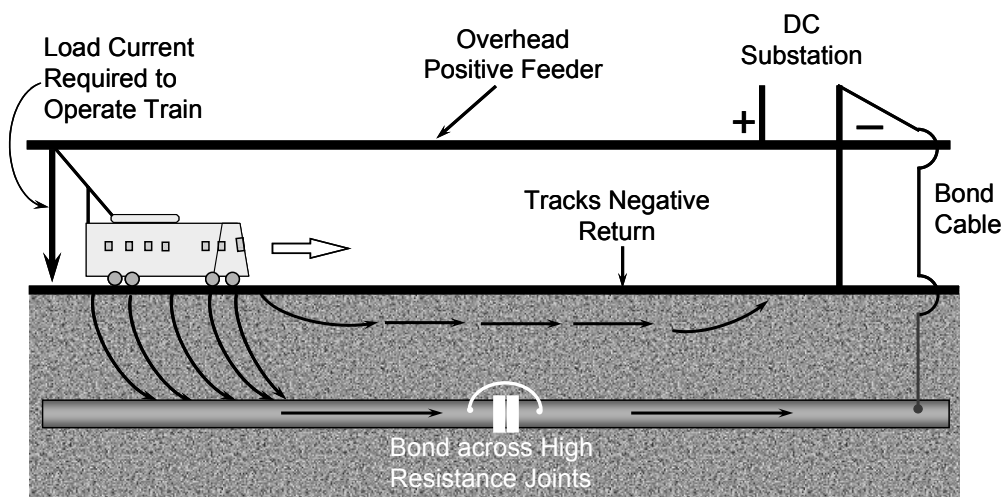


Figure 7.13 Installation of Metallic Bond

When installing metallic bonds, the following should be considered:

- Unidirectional control devices, such as diodes or reverse current switches, may be required in conjunction with the metallic bond if fluctuating currents are present. These devices prevent reversal of current flow.
- A resistor may be needed in the metallic bond circuit to control the flow of electrical current from the affected structure to the interfering structure. At the proper bond resistance, the discharge of interfering current from the structure to electrolyte is stopped.
- If cathodic protection exists on the interfering structure, attaching metallic bonds can reduce the magnitude of protection. Supplementary cathodic protection may then be required on the interfering structure to compensate for this effect.
- A metallic bond may not perform properly in the case of a cathodically protected bare or poorly coated pipeline that is causing interference on a coated pipeline. A metallic bond can increase the current discharge. Coating the bare pipe or installing local galvanic anodes on the coated pipe may reduce interference effects.

Single Bond Problem

If after doing all that is practical to minimize the accumulation of stray currents on structures it is necessary to control the stray current, a bond may be required. If there is a definite location (i.e., structure such as the substation on the trolley system) of current discharge, it is frequently possible to design a metallic bond through which this current can be returned to the traction system or, in the case of an industrial operation, to the power source (Figure 7.14). This requires accumulating certain data and calculating the needed bond resistance. Mitigation of dynamic interference is not part of this course but is covered in an separate “Interference” course.

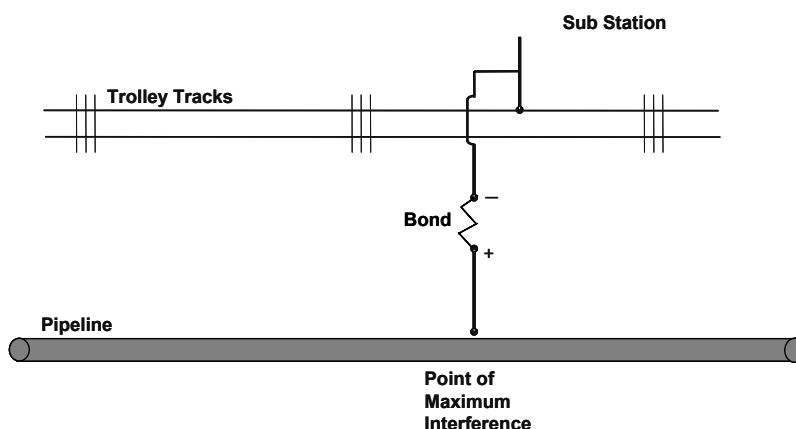


Figure 7.14 Solution of a Single Bond Problem

In relatively simple cases where a single source of stray current is involved, a trial-and-error solution may be possible. If you are only interested in eliminating the corrosive changes in potential caused by the source using a bond connection, then a variable resistor of adequate current-carrying capacity is inserted at the proposed bond location. The value of resistance is slowly reduced while the structure-to-electrolyte at the most critical location is observed. When the structure-to-electrolyte potential of the interfered-with structure at the most critical location is returned to normal, the correct value of resistance for the bond has been set.

Typically, it is desirable to use a resistance bond instead of a solid bond for the following reasons:

- The resistance bond limits the amount of current for the structure being protected.

- The resistance bond must be of low enough resistance to ensure that the stray current return is using this metallic path rather than the electrolyte.
- Resistance bonds are subject to damage by high current surges and therefore must be inspected frequently (see Chapter 8)

Controlling the Direction of Stray Current Through the Bond

Sometimes the direction of stray current through the bond is in the desired direction for much of the time but not all of the time. In these cases, stray current is toward the source when the structure to be protected is discharging current (corroding) and the reverse when the structure is receiving stray current. Stray current flow onto the structure is not desirable since it causes a discharge point at some other location(s). Diodes or reverse-current switches are used to prevent the reverse flow. The resistance to the forward current created by these devices must be included in the bond calculations.

Reverse-Current Switch

With dynamic stray current sources the direction of current through a bond could reverse causing accelerated corrosion. A diode can be installed to prevent this but it may be slow to respond. A relay can be installed that will open or reverse current. A combination of a diode and a relay reduces the disadvantages of each. Another solution may be a potentially controlled rectifier that controls the current in a forced drainage bond as shown in Figure 7.15.

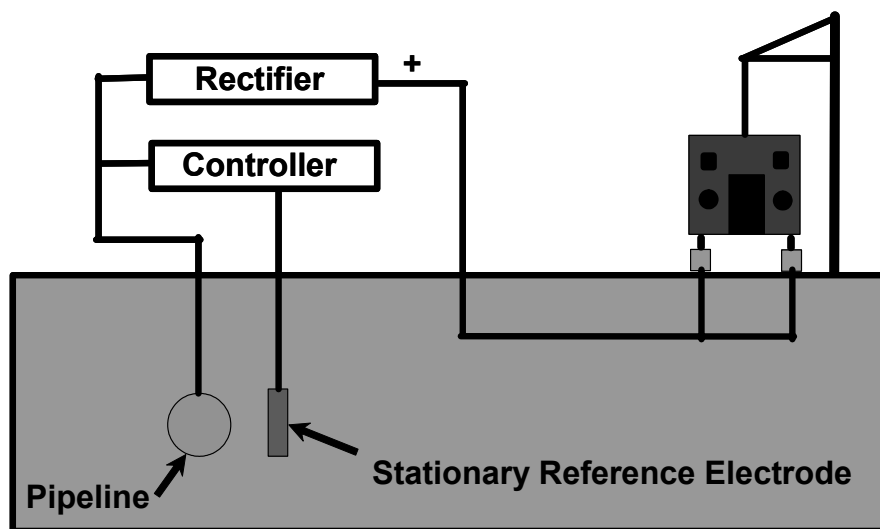


Figure 7.15 Forced Drainage Bond

Controlling Stray Current Through Cathodic Protection

Stray current can safely be returned to its source through a cathodic protection system. An example using a sacrificial (galvanic) anode is shown in Figure 7.16.

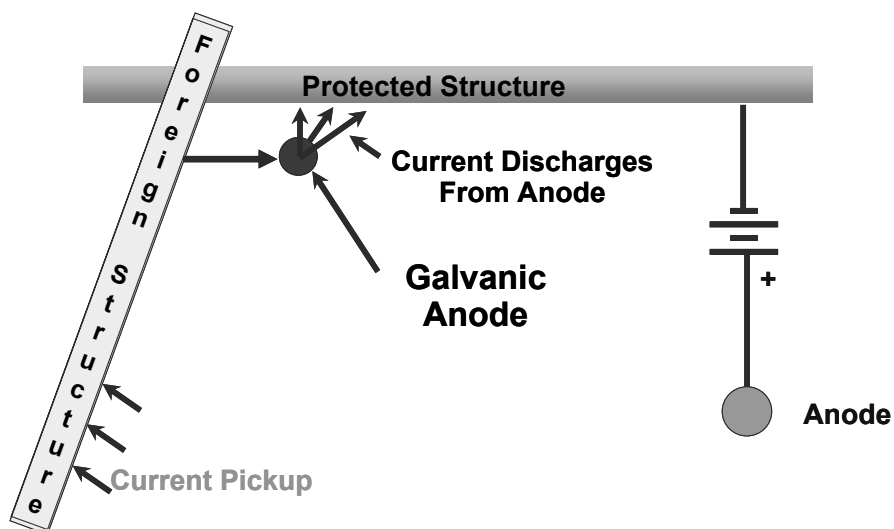


Figure 7.16 Galvanic Anodes

Coating

Coating of a known current pickup area can reduce the amount of stray current but the major portion of the anodic gradient should be coated (see Figure 7.17). Do not coat areas of current discharge as this will cause accelerated pitting at the small coating holidays.

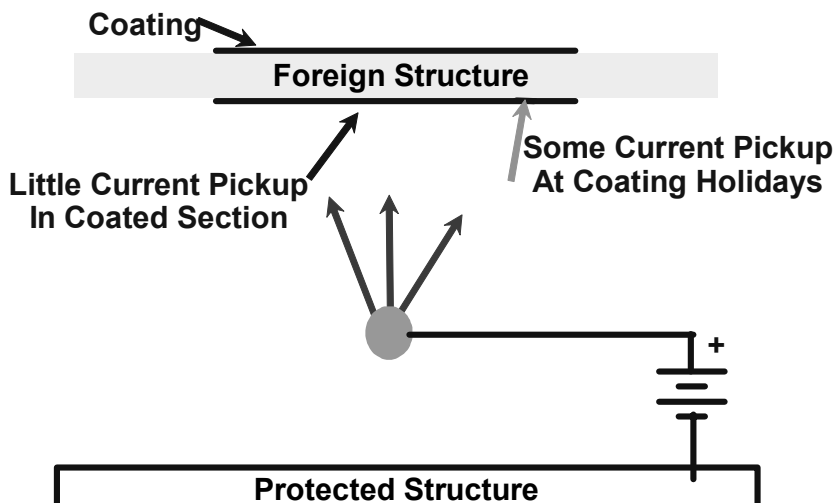


Figure 7.17 Protective Coatings

AC Testing and Mitigation

Introduction

Increased difficulty in obtaining utility rights-of-way and the concept of utility corridors have brought many underground structures, and pipelines in particular, into close proximity with electric power transmission and distribution systems. The electromagnetic field created by the alternating current expands and collapses and changes direction 120 times per second (Figure 7.18).

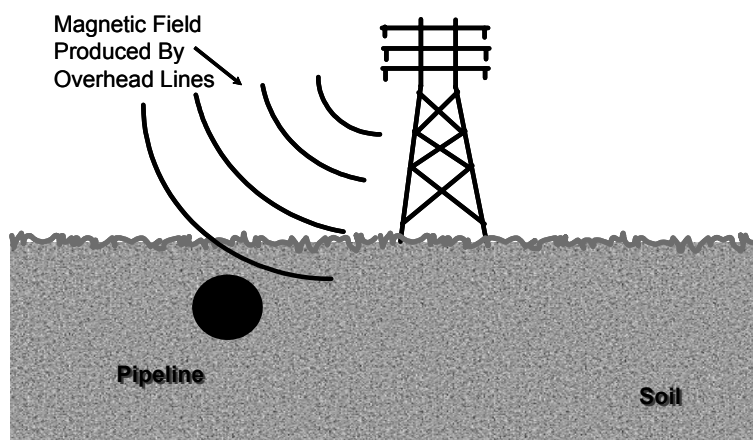


Figure 7.18 AC Interference on Pipeline from Changing Electromagnetic Field

Any metallic object subjected to an alternating electromagnetic field will exhibit an induced voltage. In addition, power conductor faults to ground can cause substantial fault currents in the underground structure.

There are three basic methods by which AC currents and voltages appear on metallic structures near AC power lines. These methods are as follows:

- Electrostatic coupling, where the structure acts as one side of a capacitor with respect to ground. This is only of concern when the structure is abovegrade (e.g., pipeline supported on skids).
- Electromagnetic induction, where the structure acts as the single-turn secondary of an air-core transformer in which the overhead power line is the primary. This type of induction may occur when the structure is either above or below ground.
- Resistive coupling, where AC power is transmitted to ground then flows on and off the underground structure.

Stray alternating currents can cause corrosion on metallic structures, although the amount of metal loss is less than an equivalent amount of DC current discharge would produce. For instance, 1 A DC discharge results in a loss of approximately 20 lbs of steel in one year, while one ampere of AC would consume less than 1 lb. The corrosion weight loss varies depending on the metal and the alternating current density. For instance, aluminum can exhibit a weight loss of approximately 40% of the DC equivalent at AC densities greater than about 40 mA/cm².

Even though the corrosion weight loss for AC currents is less than for equivalent DC currents, the magnitude of AC stray current is often large—hundreds of amperes under electromagnetic induction and thousands of amperes during power line faults. These high current levels can produce a shock hazard for personnel and can damage the structure and related equipment, such as cathodic protection facilities.

Electrostatic or Capacitive Coupling

Any two materials separated by a dielectric material can be considered as a capacitor. Capacitance is the ability to store electrical charge between two conductors relative to the voltage between the conductors. In this case the air is the dielectric and the power line is one conductor while the pipe or equipment is the other conductor.

Injury is more likely from an uncontrolled reaction to a shock rather than electrocution due to this couple.

This coupling is of most concern on aboveground equipment or pipelines such as during construction or maintenance of the pipeline. During these operations a qualified person should be on site to monitor the AC voltage and install grounds or bonds around open sections of pipe as necessary.

Electromagnetic Induction

The most important AC-induced interference current occurs as a result of electromagnetic induction as illustrated in Figures 7.19 and 7.20. Charges in the pipeline are alternately separated toward opposite ends of the pipeline. The resulting stray current magnitude is directly proportional to the phase currents ($I\Phi$) and their relative magnitudes and to the length (L) of mutual exposure; it is inversely proportional to the relative distance (d) between the structure and the power line conductors.

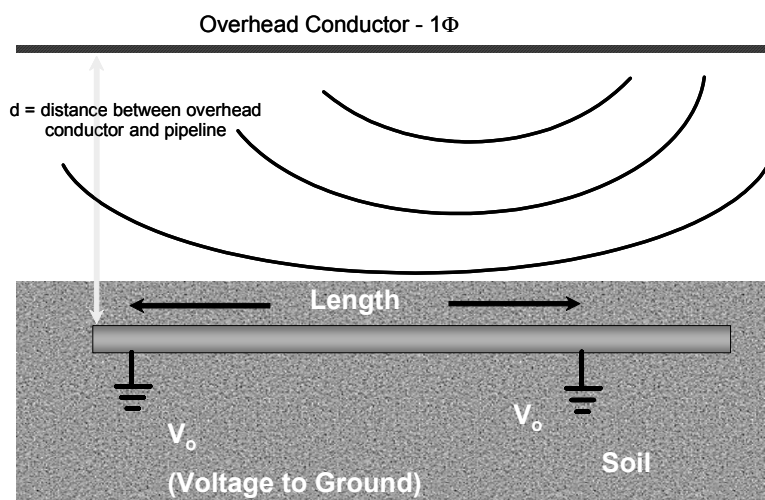


Figure 7.19 *Electromagnetically-Induced AC Voltages*

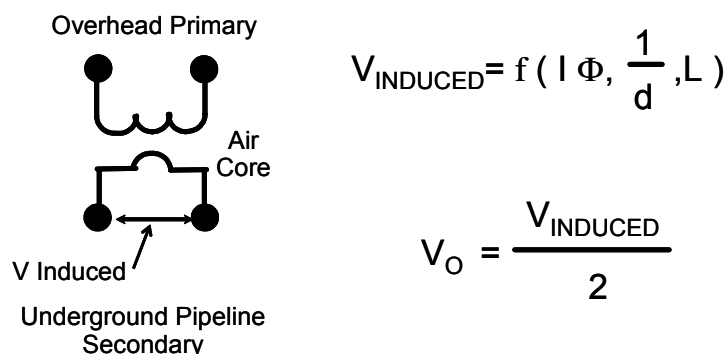


Figure 7.20 Electromagnetically-Induced Voltage Analogy

The induced voltage does not directly depend on the power line voltage; therefore, relatively low voltage AC power systems can produce electromagnetically-induced currents. In particular, single-phase heavily loaded AC power distribution lines can produce significant AC stray-current activity.

The pipe acts as a single-turn secondary of an air-core transformer, and the overhead AC power lines are primary (see Figure 7.21). The induced voltage (V_{induced}) appears across the ends of the pipe. The voltage to ground (V_{ground}) at each end of the structure is one-half the total induced voltage.

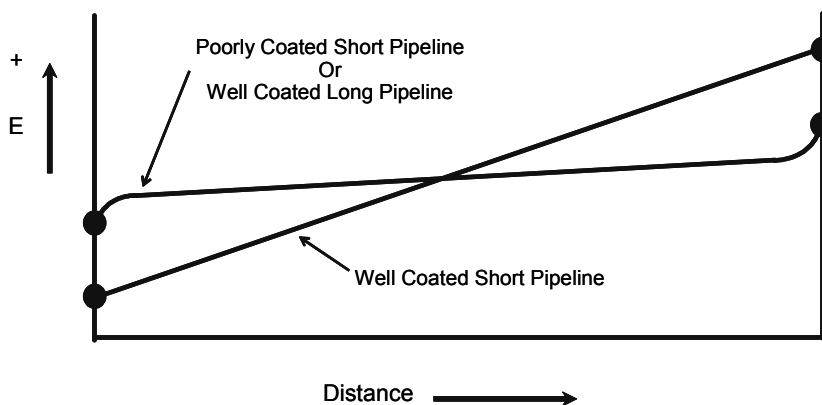


Figure 7.21 Electromagnetically-Induced Voltages on a Parallel Pipeline

For a short, well-coated structure that is not electrically lossy (i.e., causing attenuation or dissipation of electrical energy), the induced voltage profile with distance is linear. However, for poorly coated or very long, well-coated structures the voltage profile is nonlinear and the induced voltage peaks are of a lower magnitude. The induced voltage peaks appear at any electromagnetic

field or pipeline discontinuity. For example, where a pipeline closely parallels a power line for some distance, induced voltage peaks would be expected where the power line and pipeline separate. Under such circumstances, the induced voltage effect can extend some distance along the pipeline from the power line right-of-way.

Measuring the structure's AC voltage with respect to earth can easily identify interference currents of an AC origin. The reference electrode used for cathodic protection measurements can be used as the ground contact. It is prudent to measure both AC voltage and DC potentials with respect to earth on all structures in close proximity to power lines. Typically, the DC potentials will be more positive at the AC voltage peaks than in the absence of AC interference.

Resistance or Conductive Coupling

During power line faults to ground, large AC currents can be transmitted to the earth through resistance coupling and, subsequently, into nearby underground structures. These currents, which can be several thousand amperes, can cause substantial physical damage to structure coatings; in extreme cases where the AC density is high, steel piping has been known to melt. Normally, these faults occur infrequently and are of short duration; therefore, they do not represent a serious risk to operating personnel.

AC Voltage on Pipelines

Hazardous AC voltages can occur on a structure as a result of induction, ground return currents, or faulted power circuits. In cases where a structure or test leads parallel power transmission circuits, significant AC voltages may be encountered.

If an AC voltage is near or is in excess of 15 V, the structure is considered hazardous and personnel working on the structure must be advised that a hazardous situation exists. The owner or supervisor must also be advised that steps need to be taken to reduce the hazardous voltage.

If the AC voltage is determined to be less than 15 V, no specific action is necessary. However, be aware that unlike DC potentials the AC voltage changes with the load on the power line so that it can increase from when measured to later in the day. Therefore contact the power company to find out what percent of load they were operating at when the readings were taken. This will indicate the AC voltage that can be expected at full load conditions.

Whenever an AC voltage is close to 15 V (e.g., 12 V_{AC} to 14 V_{AC}) the same action should be taken as if it were 15 V_{AC} or greater.

Measurement of AC Voltage-to-Ground

The measurement of an AC voltage-to-ground is similar to a DC structure-to-electrolyte potential in that the voltage is measured between the structure and a reference electrode in the ground. There are significant differences including:

- The voltage measured may be hazardous and safety is of great concern. Do not touch any metal directly or through the meter leads/clips until it is established that there is no hazardous voltage.
- The reference electrode can be any bare metal but if a structure-to-electrolyte potential is also to be taken then a standard reference electrode can be used.
- The exposed portions of the reference electrode must not be touched and the electrode is to be installed first. If using a CSE then the top should be taped to prevent accidental contact.
- Induced AC voltage changes with the power line load and/or power line fault conditions.
- AC voltages change on aboveground pipelines under construction as the pipe length increases during the welding operation.
- Induced AC voltages can be expected to be higher at the discontinuities between the pipeline and the power line, that is, where they come together, separate, or cross.
- The measurement should duplicate step voltages. Therefore the electrode should be about one (1) meter away from the closest contact point(s) above ground on the structure. (Unlike structure-to-electrolyte potentials where the reference electrode is to be placed close to the structure where it enters the ground.)

Measure the AC structure-to-ground voltage first to make certain that it is safe to continue to work.

First, place the electrode into the ground approximately one (1) meter from the structure contact point then contact the structure with an insulated probe and turn the meter to AC Volts.

If the AC voltage is 15 V or greater, cease work until the AC voltage has been mitigated or, if qualified, proceed with further investigation into the cause and best means of mitigation. At no time should the structure be contacted under these conditions. Qualified personnel are to install temporary grounds, grids and/or nonmetallic fences at the work area or where the public can contact the structure until permanent protective equipment is installed.

Mitigation of AC Interference

The close proximity of structures to AC power lines and their sharing parallel paths for relatively long distances is the principal cause of stray AC. If the structure is remote from the power line(s), the interference can be virtually eliminated. Obviously, this method of mitigation is practical only at the preconstruction stage of either the power line(s) or the structure. Otherwise, the mitigation must be accomplished by alternative methods.

AC mitigation methods include:

- Significant separation between pipe and HVAC system
- Ground pipe using distributed galvanic anodes
- Grounding pipe using a metal such as zinc, magnesium, steel, or copper. DC decouplers such as a capacitor, polarization cells, or polarization cell replacements (PCR) connected between pipe and a separate “grounding” structure will reduce the CP requirements when a more noble ground is tied directly to the structure. A DC decoupler allows AC current to pass but blocks DC current.
- Protective devices for electrical isolating devices such as flange kits or joints.
- Step-and-touch protection systems (gradient mats or grids)

Figure 7.22 shows that the induced voltage is reduced if the structure becomes electrically conductive to earth. A well-coated structure would normally result in higher induced voltages.

On short lines, this effect can be remedied by using distributed sacrificial anodes on the structure; the anodes will not only be sufficient to provide cathodic protection current but will also simultaneously lower the resistance of the structure with respect to earth. Another approach is to use a zinc strip or ribbon anode parallel to the structure as the grounding method.

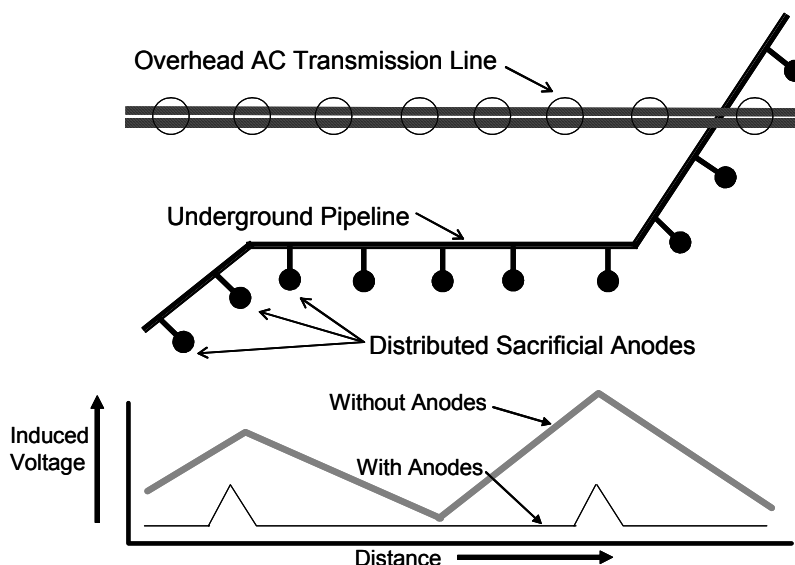


Figure 7.22 Mitigation of AC Interference Using Distributed Galvanic Anodes

On longer lines, the approach is to install grounds at the higher voltage peaks, normally at the discontinuities. In Figure 7.22 a similar effect could likely be achieved by installing larger grounds at the two voltage peaks.

Even with the grounds, hazardous voltages may still exist at other separation points and require more extensive grounds to reduce the AC voltage to 15 V or less.

Corrosion personnel must be aware of the possible shock hazard that can appear on a structure subjected to AC interference. Precautions such as nonmetallic dead-front test stations should be incorporated into the cathodic protection systems, and nearby cathodic protection rectifiers should be protected from AC fault currents with devices such as capacitors, polarization cells, and zinc grounding cells.

Bare casings interconnected through a capacitor bank, polarization cell replacement, or a polarization cell to the structure also are effective in mitigating AC interference.

Polarization Cells

Figure 7.23 shows a polarization cell used as a DC decoupler that allows AC current to pass to a ground while blocking the DC current intended for the cathodic protection of the structure. The cell consists of a container filled with a potassium hydroxide solution (the electrolyte) into which stainless steel plates are immersed and alternately connected to the cell terminals. One of the cell terminals is connected to the structure and the other to ground (or if used to protect an insulating joint from AC, the terminals are connected across the insulating joint).

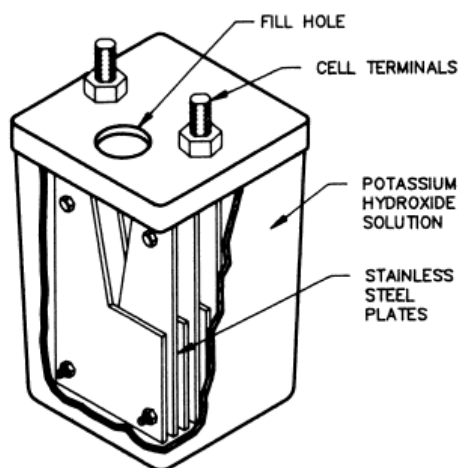


Figure 7.23 Polarization Cell

The cell acts as an electrochemical switch to shunt voltage to ground. Under normal conditions, the plates of the cell polarize and allow normal cathodic protection potentials to exist. As the applied voltage across the cell increases from either AC or DC, the polarization film on the plates breaks down and the cell shunts current. The cells must be properly vented (to allow gases generated during operation to escape) and periodically inspected to ensure adequate electrolyte levels.

Semiconductor Devices

Solid state devices are available that block the low-potential DC cathodic protection current from leaking across an insulating device while still providing instant protection from high-voltage spikes and induced AC. These devices do not involve caustic liquid electrolytes and are a low-maintenance device. Figure 7.24 shows a semiconductor-type device.



Figure 7.24 Semiconductor Device for AC and High-Voltage Fault Control (courtesy of Dairyland Electrical Industries)

Ground Mats

Ground mats may be required to protect personnel from electric shock while working on well coated pipelines. Induced voltage from AC power lines and lightning strikes can create large voltage gradients between a pipeline and earth.

Ground mats are metal conductors placed in the soil around locations where a person may come in contact with the pipeline. Test station wires, line valves, and other fittings are examples of where a hazard may exist. The ground mat is connected to the pipe thus assuring that the pipe and the ground in the immediate area are at the same electrical voltage. They are not intended to be an electrical ground as they are installed close to the surface often in high-resistivity soil or frost.

Ground mats can be made from any metal. A more active metal such as zinc or magnesium is used to have minimum impact on the cathodic protection system. Other metal such as copper or steel can be used but will add significantly to the current required for cathodic protection due to their large area of earth contact. If the mats are constructed of copper or other noble alloy or metal, adequate cathodic protection must be applied to eliminate the corrosive galvanic couple or isolated using a DC decoupler. Figure 7.25 illustrates how ground mats are applied with the rings becoming consecutively deeper at about 15° away from the structure.

It should be noted that if zinc or magnesium is used as a gradient mat around a test station, then the instant OFF potential is no longer valid as all sources of DC current have not been interrupted.

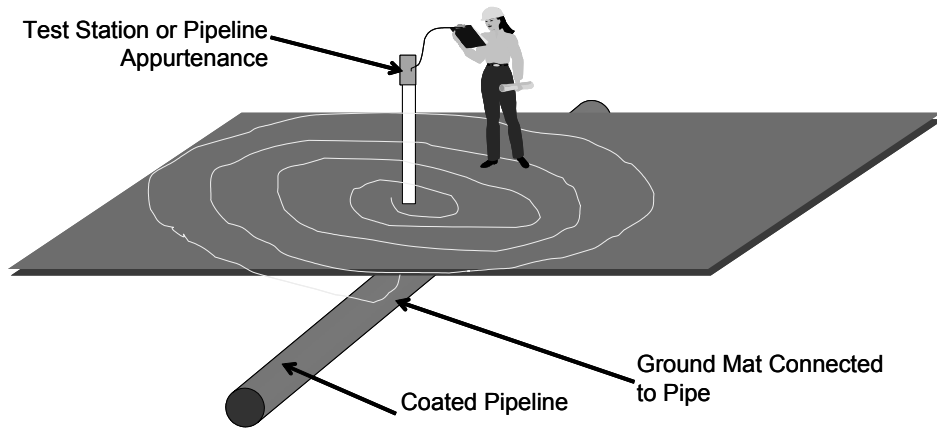


Figure 7.25 *Typical Ground Mat Used to Protect Personnel from Electric Shock*

Major Objectives of a Cathodic Protection System

The following objectives must be accomplished in a cathodic protection system that adequately prevents corrosion:

- Provide sufficient current to the structure to be protected.
- Distribute this current such that the selected criteria for cathodic protection are efficiently attained.
- Minimize the interference currents on nearby underground structures and from other sources of DC current.
- Have an anode system with life commensurate with the required life of the protected structure, or provide for periodic rehabilitation of the anode system.
- Allow for changes in current requirements with time.
- Ensure anodes are not disturbed or damaged and other structures have not been installed close to them.
- Ensure that the CP system operates continuously.

Monitoring

The objective of a cathodic protection system is to ensure that it continues to operate at the intended levels. Frequent inspections will be the first step in keeping the time without protection to a minimum. The second step is to have a quick response plan to correct trouble as it is found.

A complete monitoring program involves a detailed field survey over the entire system with brief inspections in between. The detail survey ensures that the conditions have not changed, and the current output is still adequate to meet a cathodic protection criterion or, if not, to make the appropriate adjustments. The routine readings must be adequate to confirm that the system is continuing to operate at the levels expected.

Detailed Field Survey

Electrical measurements are normally taken at the source(s) of cathodic protection and throughout the structure at close enough spacing to confirm that a criterion for protection is met. If a portion of the system is delinquent then additional testing is required to either locate the trouble or to determine the additional current required to meet a criterion.

Regulated industries are required to meet minimum standards and inspection intervals that will vary depending on the country (Table 8.1).

Pre-Survey Planning

Before starting the field survey, all available information about the structure should be assembled and studied. This will furnish valuable data on conditions to be expected during the survey.

The following items of information are typical of those that should be accumulated prior to planning and starting the field survey, especially the first survey:

- Structure material(s): example, steel (including grade of steel), cast iron, wrought iron, or other material and their known electrical resistance.
- Is the structure bare or coated? If coated, what is the coating material and what coating specifications were used?
- If it is an existing structure, is there a leak record? If so, information on the location and date of each leak occurrence may indicate the more serious problem areas.
- Structural dimensions such as wall thickness and weight per foot
- If applicable, sizes of casing pipe with wall thickness or weight per foot; grade of steel used; data on insulators used between pipe and casing; specifications of casing end seals; for coated casing pipe, type of coating, and application specifications.

- Location and construction details of all corrosion test points installed on the structure. If no corrosion test points were installed, determine locations where contact can be made with the structure for test purposes.
- Is the structure all welded construction or are mechanical couplings used?
- Location of branch taps or associated structures
- Location of any electrical isolating flanges or couplings used to sectionalize the structure or to electrically isolate it from other portions of the system or from foreign structures.
- Details and location of the cathodic protection system.
- System maps
 - Location of structures of other ownership that may be affected, including the location of cathodic protection current sources.
 - Location of test stations and other facilities
 - Location of possible sources of manmade stray current (such as DC electric transit systems or mining operations)
 - Location of AC power services if additional current capacity is suggested
- Does any part of the structure closely parallel (within 200 ft or so) high-voltage (HVAC or HVDC) electric transmission lines? If so, what is the length of such exposure? How close is the structure to the towers? What voltages and currents are associated with the AC power line? What method is used for grounding the towers? Is any grounding in place for the pipeline? These factors aid in determining whether AC voltages may be induced on the structure during construction, maintenance or during normal operation of the structure. If induced AC potentials are possible, the structure should be considered a safety hazard and contact with it avoided until measurement of actual AC potential.

- Is the structure operated at elevated temperatures or will it be in the foreseeable future? (High temperatures deteriorate coatings and increase corrosion rates.)

Survey Methods

After obtaining background information on the structure, the actual field survey may be organized to use several or all of the following procedures (either separately or combined). The methods selected and the relative importance of data obtained from each method will depend on the particular situation at hand.

- ON/OFF or ON Structure-to-electrolyte potential survey
- Line current survey
- Location of faulty isolation
- Road/railroad casing tests if applicable
- Coating conductance tests if applicable
- Inspection for corrosion

Sometimes nothing will satisfy the corrosion engineer except having an actual look at the structure being surveyed. Actually, this is an acceptable and desirable procedure for evaluating the severity of corrosive areas detected by abovegrade surveys. “Hot spot” corrosion (local areas of corrosion) found during a survey may be uncovered and inspected.

If areas are found where structure coatings have unusually low resistance values, bellhole inspections may be in order to trace causes of the coating damage. This may be particularly valuable with older coatings to determine the nature of deterioration and as a guide to selecting materials for future coating projects.

- Electrical resistivity of the environment if applicable

In addition to being a valuable aid for interpreting the severity of corrosive areas, a resistivity survey is extremely helpful in later selection of sites for cathodic protection installations.

- Determination of acidity or alkalinity of the environment

In many areas, an environment is approximately neutral (pH 7). Some locations have unusual environmental conditions that could be either alkaline or acidic.

It may be of value to check the soil pH. The results could have considerable effect on the locations selected for future cathodic protection rectifiers or galvanic anodes. A particularly acidic condition could indicate the need for a relatively high current density to maintain cathodic protection. This could make it desirable to locate cathodic protection installations at or near the area of high current requirement.

- Determination of conditions suitable for anaerobic bacterial corrosion

Certain bacteria that exist under anaerobic conditions (absence of oxygen) can reduce sulfates and consume hydrogen in the process. Consumption of hydrogen at the structure surface depolarizes the steel at cathodic areas and permits more rapid consumption of the metal by galvanic corrosion cells. The bacteria then do not directly attack the structure but create conditions conducive to more rapid attack by existing corrosion cells, which, normally, are partially stifled by the development of a polarization film of hydrogen.

Areas where anaerobic corrosion is suspected may be exposed for examination. If anaerobic bacteria are present and active, a layer of black iron sulfide will be found at the structure surface. The deposit would be expected only at coating defects on structures having a bonded coating. If this black substance is iron sulfide and is treated with a dilute solution of hydrochloric acid, hydrogen sulfide gas will be released, which can be recognized by its characteristic rotten egg odor.

The practical effect of anaerobic bacterial activity on the application of cathodic protection is an increase in the amount of current required to maintain cathodic protection.

- Evaluation of current requirements for cathodic protection

During a survey, it may be desirable to conduct a specific test to determine the additional current requirements if a cathodic protection criterion is not achieved. Such a test consists of forcing direct current to flow from a

temporary anode bed to the structure being studied and determining how much current will be needed to achieve a specific level of polarization.

- Use of recording instruments to study dynamic stray current conditions
- Earth Gradient Measurements

Routine Readings

The method of routine inspection will vary depending on the type of structure and cathodic protection system. A plan must therefore be developed and tested to ensure that the objectives are met. Such a plan would include:

- The type of cathodic protection system
- The type of measurements to be taken
- The location where the readings are to be taken
- The type of equipment to take the measurements
- The frequency of the readings.

Sacrificial (Galvanic) Anodes

Most sacrificial (galvanic) anode systems can be routinely inspected by taking reference potential measurements at critical locations throughout the system. Since these systems usually provide low current outputs, a problem such as a shorted isolation will have a major impact on the potentials. Reference potentials are essentially a structure-to-electrolyte potential although for this purpose a large unprotected structure can be used as a reference and the data converted to a standard reference electrode. An example may be the use of a large unprotected metal water main by taking a reference potential across an isolating feature between it and a gas distribution system. A reading with a nonstandard reference should not be used to confirm a criterion but can be used to predict a change in the level of protection.

When another large bare structure is accidentally connected to a structure protected by a galvanic anode, the structure-to-electrolyte potential will naturally become less electronegative or more electropositive. This change in potential then increases the difference in potential between the structure and the anode thus increasing the driving voltage and in turn increasing the current.

Impressed Current Systems

A combination of inspections of the DC power source and reference potentials are often employed for impressed current systems. In the case of a transmission pipeline where few external problems are expected, then an inspection of the DC power sources may be sufficient.

Where there is a possibility of shorted isolation or stray currents then reference potentials should also be taken.

The readings taken to confirm that a DC power source is operating properly should include:

- DC Current
- DC Voltage
- Tap Setting

These are described in more detail in Chapter 4. The DC current is the prime measurement but the DC voltage, when used to calculate anode resistance, will help predict future anode failures. The initial increase in resistance is slow but as the few remaining anodes fail, the resistance increases at a greater rate. The tap setting will indicate if someone authorized or has not been adjusting the taps.

If a DC power source is not accessible during portions of the year, then reference potentials taken at a “Control Point” can be taken. A “Control Point” is located such that the DC power source (rectifier) in question has a large influence on the potentials. The influence should be confirmed by either turning all rectifiers influencing the area off in turn and taking ON/OFF potential measurements or by installing interrupters at different cycles in the rectifiers and taking a datalog at the Control Point. In this way a prediction of the operating status of the rectifier can be made by an analysis of the Control Point potentials. Another factor to consider is that structure-to-electrolyte potentials may change with the seasons.

A shorted bare structure will likely exceed the capacity of the impressed current cathodic protection system and cause an electropositive shift in the structure-to-electrolyte potential. Since the anode resistance is the major component of the total resistance in an impressed current system a small reduction in the structure resistance is not likely to have a noticeable change in the current output of the DC power source.

Inspection Intervals

Regulated industries are required to inspect the cathodic protection systems and take sufficient readings at intervals to ensure that it is operating as intended. This practice is of value to any cathodic protection system as it helps ensure that the cathodic protection system continues to operate. The more frequent the reading interval, the more likely the structure will receive protection for more of its life. To illustrate this point, if a rectifier goes off just after it is read and is not discovered for two (2) months and this happens once each year then after twelve (12) years, the pipeline has been without protection for an accumulated period of two (2) years. This possible outage period can be reduced to an accumulated time of one (1) year/twelve (12) years by reading the rectifiers monthly.

A summary of the inspection intervals required by different regulations is given in Table 8.1

Table 8.1 Cathodic Protection Inspection Intervals for Regulated Pipelines

Regulation or Standard	Detailed Survey Frequency	Rectifier Inspection Frequency	Interference Control Drainage Bond Frequency
USA DOT 49CFR192 DOT 49CFR195	Once per calendar year not to exceed an 18-month interval	Six times per year not to exceed 2½-month intervals	Six times per year not to exceed 2½-month intervals
Canada CSA Z662 (CGA OCC-1)	Annual	Monthly not to exceed 6 weeks	Bimonthly
Europe ISO 15589 Part 1	Instant OFF annually except stable systems can extend to every 3 years with ON potentials in between	1 to 3 months depending on conditions such as lightning, stray currents, construction	Monthly
	Less frequent measurements considered based on results of specialized surveys		
Industry Practice NACE Standard RP0169	Annually. Longer or shorter periods depending on safety factors, etc.	2-month intervals	2-month intervals

Records

Complete and accurate records are mandatory. There are technical, historical, and legal reasons why records must be kept. You, as a CP Technician, must accept full responsibility for the accuracy and completeness of both your records and those of personnel under your supervision.

A great deal of time and effort has gone into collecting this information and it is of no use if it is not documented properly.

Records for Technical Purposes

These records may be used for:

- Technical support of cathodic protection (CP)
- Data that must stand up to a regulator's scrutiny if a regulated industry
- Evaluations of coatings
- Stray current analysis
- Assessment of CP capacity
- Location of CP equipment relative to structures

Records for Historical Purposes

We must recognize that throughout the life of the system others will be referring to these records. Full and complete explanations are required as they may be reviewed at a time when personnel and conditions have changed. Data that seems obvious today may be confusing at a later date. Regulated industries must keep their records for a specified period of time or for the life of the structure. Regardless, historical information is of great value in:

- an assessment of the life of the CP system
- changes to the operation that have occurred
- troubleshooting
- determining future requirements
- an External Corrosion Direct Assessment (ECDA)¹
- an Internal Corrosion Direct Assessment (ICDA)

Records for Legal Purposes

Although we hope that an incident never occurs, we must be prepared to show due diligence and be prepared for a legal defense. For this reason records must be impeccable with no room for criticism. Some items that are necessary to include before filing the notes include:

- Are the values recorded correctly?
- Has polarity been assigned to all readings?

¹ See NACE Standard RP0502, "Pipeline External Corrosion Direct Assessment Methodology," a four-part program to assess external pipeline integrity especially for pipelines that are not suitable for an intelligent tool.

- Are the units clearly indicated (Volts, Amperes, etc.)
- Where applicable, is the reference electrode clearly noted?
- Are the exact reading locations listed?
- Are the structures on which the readings are being taken described?
- Are drawings and maps accurate and up to date?
- Have descriptions of troubleshooting work been included?
- Has inspection data been documented?

Field Data Sheets

Tester's name, date, time, and weather conditions should always be noted on the data sheets. Weather conditions can affect the data collected and help explain the data collected in the field.

Measurements must include the accurate recording of the:

- Value
- Polarity
- Units
- Type of reference electrode, where applicable

Without all of the above indicated for each measurement, the data is of little use in industry or for legal purposes and will be considered incorrect in this course!

Sketches showing the layout of structure(s) should be completed along with the location of measurements with the polarity of measurements indicated. The name and serial numbers of all instruments used should be included in the data sheets. Always indicate unusual site conditions. Data must be legible if it is to be of any value.

Computer Records and Spreadsheets

Nearly all corrosion records today are kept on computer databases. Usually these databases show the test points, date of last test, the measurement itself, whether or not the data met the selected criterion, and when the next test is due. Printouts are then generated at the appropriate times for technicians to take into the field for the next scheduled tests. The latest data are then entered into the database. Spreadsheets can also be generated showing test points that do not meet criteria. These can be taken into the field for troubleshooting.

If you have been collecting data on a computer datalogger, the data can be entered directly into a computer. Graphs and spreadsheets of data can be generated, or the data can be downloaded into the company computer system.

Large companies, particularly those with operations spread over a large area, are now using Internet access for corrosion control data. This makes it possible for all data in a technician's area to be available without having to have a large computer system in local offices.

Facility Maps and Documentation

Companies that operate underground plants, such as pipelines or cables, maintain atlas maps showing the location of structures, test points, cathodic protection installations, and many other data. The same is true of many large industrial plants, refineries, college campuses, and similar facilities. You need to be familiar with what these maps show and be able to work with them in the field.

Documentation of your work is essential. Those responsible for updating facility maps will depend on your information to keep the maps current or to generate new maps. Consequently, as-built drawings of corrosion control installations must be accurate. Likewise, if you are involved with repairs of structures or corrosion control components, accurate information must be turned in. Accuracy in your work documentation is just as important as accuracy in your data sheets, as previously discussed above under Data Sheets.

Records of Related Information

Direct Inspection

Whenever an underground structure is exposed an inspection for corrosion should be made and the data recorded even though no corrosion is found. This information can then be used to complete future analysis of the effectiveness of cathodic protection systems and of pipeline integrity.

Leak Frequency

Records of corrosion-related leaks are invaluable in assessing the effectiveness of the program and the integrity of the structure (Figure 6.60). Maintaining leak record curves is a method that can be used to prove the effectiveness of cathodic protection and is also useful for owners of structures that are not

regulated by a government agency. All information related to the type and cause of the leak should be recorded and maintained.

In-Line Inspection

The results of in-line inspection and subsequent dig inspections are extremely valuable in confirming the effectiveness of the corrosion control program in addition to confirming the pipeline integrity. Unfortunately, this does not confirm this effectiveness until after corrosion has had an opportunity to proceed therefore it should be used in conjunction with other tests. Once it has confirmed that no corrosion is occurring at the potentials that have existed, then these potentials can be argued as an effective criterion for those particular sections of pipeline.

Storage

Data must be stored in a predefined fashion that allows it to be easily retrieved for future reference. The storage time for regulated industries is defined by their regulations, however, it is recommended that this data be kept for the life of the system for both regulated and unregulated systems. As discussed before this data can be invaluable for ECDA.

Regulatory Requirements for Records

Each country or local region has its own regulations and the CP technician must be familiar with the regulations that apply to the facility in that particular area. For example, those working on regulated systems must be familiar with the following applicable codes and standards.

Leak Records

Structure	Federal Regulation	Storage
USA		
Gas pipeline	Title 49 CFR Part 191.23(a)(1)	Life of pipeline
Gas pipeline	Title 49 CFR Part 192	
Hazardous liquids pipe	Title 49 CFR Part 195.55 (a)(1)	Life of pipeline
Hazardous liquids pipe	Title 49 CFR Part 195.404(c)(1)(2)	
Canada	CSA Z662	Life of pipeline
Europe	ISO 15589 Part 1	Retained

Pipeline Examinations

Structure	Regulation/Standard	Storage
USA		
Gas pipeline	Title 49 CFR Part 192.491	Life of pipeline
Hazardous liquid pipe	Title 49 CFR Part 195	Life of pipeline
Canada	CSA Z662	Life of pipeline
Europe	ISO 15589 Part 1	

Cathodic Protection Facility Locations

Structure	Regulation/Standard	Storage
USA		
Gas pipeline	Title 49 CFR Part 192.491	Life of pipeline
Hazardous liquid pipe	Title 49 CFR Part 195.266(f)	Life of pipeline
Canada	CSA Z662 (CGA cOCC-1)	Life of pipeline

Tests, Surveys, and Inspections

Structure	Regulation/Standard	Storage
USA*		
Gas pipeline	Title 49 CFR Part 192.465(a) and (e)	Life of pipeline
Hazardous liquid pipe	Title 49 CFR Part 195.416(a)	Life of pipeline
Underground tanks	Title 40 CFR Part 280.34	Life of tank
Aboveground tanks	API RP 651	5 years
Canada	CSA Z662 (CGA OCC-1)	Life of pipeline
Europe	ISO 15589 Part 1	Retained for future reference

*Field testing, including soil resistivity, pH, current requirement tests, leak detection surveys, coating inspections, periodic tests of power sources, internal corrosion monitoring devices, stray current control devices, and coating evaluation must be kept for five years per 49 CFR Parts 192.455, 457, 461, 465, 416, 477, and 481. This information is; however, of value in future assessments and for a possible External Corrosion Direct Assessment (ECDA) therefore it is wise to keep it for the life of the system.

Useful Information

Other useful information on a system that should be maintained and updated includes:

- System specifications and practices as applicable
 - Site maps
 - Construction dates
 - Pipe, fittings, etc.
 - Coatings
 - Casings
 - Test stations
 - Electrical insulating devices
 - Electrical bonds
 - Aerial, bridge, and underwater crossings
 - Project budget
- System site conditions
 - Existing and proposed cathodic protection systems
 - Possible interference sources
 - Special environmental conditions
 - Nearby buried metallic structures (including location, ownership, and corrosion control practices)
 - Structure accessibility
 - Power availability
 - Feasibility of electrical isolation from foreign structures
- Field survey, corrosion test data, and operating experience
 - Protective current requirements to meet applicable criteria
 - Electrical resistivity of the electrolyte
 - Electrical continuity
 - Electrical isolation

- Coating integrity
 - Cumulative leak history
 - Interference currents
 - Deviation from construction specifications
 - Other maintenance and operating data
- Other
 - Smart pig data
 - Dig site records
 - Coupon data

Some of the data gathered can be analyzed using graphical or statistical methods to highlight locations needing particular attention. For example, soil resistivity data can be statistically analyzed and plotted to determine areas with particularly corrosive soils. Pit depth data can be statistically analyzed to identify areas that are severely corroded. Leak records can be plotted as cumulative leaks vs. time to identify trends and prioritize areas needing attention.

APPENDIX

Appended Documents

The following documents are appended for reference and for use in your work:

Basic Electricity Review

Basic Chemistry and Electrochemistry Review

Meter Operation Review

Glossary of Terms

“Factors Affecting the Accuracy of Reference Electrodes”, Frank Ansuini and James R. Dimond, Materials Performance, November, 1994 (NACE International, Houston, TX).

RP0169 “Control of External Corrosion on Underground or Submerged Metallic Piping Systems”

RP0285 “Corrosion Control of Underground Storage Tank Systems by Cathodic Protection”

RP0176 “Corrosion Control of Steel Fixed Offshore Platforms Associated with Petroleum Production”

RP0388 “Impressed Current Cathodic Protection of Internal Submerged Surfaces of Steel Water Storage Tanks”

RP0177 “Mitigation of Alternating Current and Lightning Effects on Metallic Structures and Corrosion Control Systems”

RP0575 “Internal Cathodic Protection Systems in Oil Treating Vessels”

RP0193 “External Cathodic Protection of On-Grade Metallic Storage Tank Bottoms”

RP0196 “Galvanic Anode Cathodic Protection of Internal Submerged Surfaces of Steel Water Storage Tanks”

RP0290 “Cathodic Protection of Reinforcing Steel in Atmospherically Exposed Structures”

RP0200 “Steel Cased Pipeline Practices”

TM0497 “Measurement Techniques Related to Criteria for Cathodic Protection on Underground or Submerged Metallic Piping Systems”

TM0101 “Measurement Techniques Related to Criteria for Cathodic Protection on Underground or Submerged Metallic Storage Tanks”

Other Reference Material

Peabody’s Control of Pipeline Corrosion (NACE International, Houston, TX 2001).

Parker, M. & Peattie, E., *Pipeline Corrosion and Cathodic Protection*, Third Edition, Gulf Publishing, 1984.

Romanoff, M., *Underground Corrosion*, NACE International Reprint, 1989.

Cathodic Protection of Steel in Concrete, P.M. Chase, Editor, NACE International, Houston, TX 1998.

Practical Corrosion Control Methods for Gas Utility Piping, Second Edition, NACE International, Houston, TX 1995.

Other Standards

Australia

Australian Standards Institute, Standard 2832

- Part 1 Pipe, Cables and Ducts
- Part 2 Compact Buried Structures
- Part 3 Fixed Immersed Structures

England

British Standards Institute

Standard BS 7361, Part 1, “Cathodic Protection: Code of Practice for Land and Marine Applications”.

Standard BS 5495 “Code of Practice for Protective Coating of Iron and Steel Structures Against Corrosion”.

Standard BS 6651 “Protection of Structures Against Lightning”.

Canada

Canadian Standards Association

Standard Z662, “Oil and gas Pipeline Systems.”

Standard Z169, “Cathodic Protection of Aluminum.”

Standard 22.1, “Canadian Electrical Code.”

Canadian Gas Association Recommended Practice OCC-1, “For the Control of Corrosion on Buried or Submerged Metallic Piping Systems.”

Germany

Standard DIN 30676, “Cathodic Protection.”

Japan

The Overseas Coastal Area development Institute of Japan, “Corrosion Protection and Repair Manual for Port and Harbor Steel Structures.

Japanese Port Authority Association, “Harbor Facility Technology Criteria and Discussion, Part 1.”

Japanese Water Piping Association, WSP-050, “Cathodic Protection Manual for Coated Steel Water Pipe.”

Norway

Det Norske Veritas Norge AS (DNV), Recommended Practice RP B401, “Cathodic Protection Design”.

Norske Standard Common Requirements Cathodic Protection, M-CR-503

Oman

Petroleum Development of Oman Standard PDO-65-12

Saudi Arabia

Saudi Aramco Engineering Standards, SAES-X-400.

United States

American Water Works Association (AWWA) Standard D104 “Automatically Controlled, Impressed Current Cathodic Protection for the Interior of Steel Water Tanks.”

American Petroleum Institute (API)

Recommended Practice 651, “Cathodic Protection of Above Ground Petroleum Storage Tanks.

Recommended Practice 1632, “Cathodic Protection of Underground Petroleum Storage Tanks and Piping Systems.”

U.S. Government, Code of Federal Regulations (CFR)

49CFR Part 192, Subpart I	Natural Gas Pipelines
49CFR Part 193, Subpart G	Liquefied Natural Gas
49CFR Part 195, Subpart D	Hazardous Liquid Pipelines
40CFR Part 280	Underground Storage Tanks

Introduction

Corrosion and cathodic protection are electrochemical phenomena. Consequently, electrical instruments are used in some corrosion testing and we need to understand various electrical terms, laws, and circuits when working with cathodic protection. This knowledge is essential for anyone entering the field of cathodic protection technology. The more important concepts are discussed in this chapter.

Electrical Terms

Electrons

Electrons are particles that carry a negative charge. They also help hold matter together, a bit like the mortar in a brick wall.

Voltage

Voltage (joule/coulomb), or *potential*, is an electromotive force or a difference in potential expressed in Volts. Voltage is the energy that puts charges in motion. This force is measured in volts, millivolts, and microvolts. In corrosion work all three units are used. The following shows their relationship:

1,000 Volts	=	1 kilovolt
1.000 Volt	=	1000 millivolts
0.100 Volt	=	100 millivolts
0.010 Volt	=	10 millivolts
0.001 Volt	=	1 millivolt
0.000001 Volt	=	1 microvolt

Common symbols for voltage are:

emf	electromotive force - any voltage unit
E or e	voltage across a source of electrical energy (e.g. battery, pipe-to-soil potential)
V or v	voltage across a sink of electrical energy (e.g. resistor)

You will be concerned with voltage when making various measurements in cathodic protection work. Among these are pipe-to-soil potential measurements, voltage drops across shunts or along pipelines and the voltage output of a cathodic protection rectifier.

Current

Current is the flow of charges along a conducting path and is measured in amperes. Current is frequently abbreviated as amps, milliamps, or microamps. In corrosion work we use all three units. The following shows their relationship:

Ampere = the common unit of current = a flow rate of charge of 1 coulomb per second. One coulomb is the unit of charge carried by 6.24×10^{18} electron charges.

1,000 amperes	=	1 kiloampere
1.000 ampere	=	1000 milliamperes
0.100 ampere	=	100 milliamperes
0.010 ampere	=	10 milliamperes
0.001 ampere	=	1 milliampere
0.000001 ampere	=	1 microampere

Common symbols for current flow are:

I	any amperage unit
mA	milliamperes or milliamps
μ A	microamperes or microamps

Direct current flows constantly in one direction in a circuit. Alternating current regularly reverses direction of flow, commonly 100 or 120 times per second.

Resistance and Resistivity

Resistance is the opposition that charges encounter when moving through a material (Ohms).

Resistivity is the resistance of a conductor of unit length and unit cross-sectional area.

The symbol used for resistivity is ρ (Greek letter rho).

Resistivity is constant for a given material and is computed by the formula:

$$\rho = \frac{R \times A}{L} \quad [1]$$

where ρ = Resistivity in $\Omega\text{-cm}$
 R = Resistance in Ω
 A = Cross-sectional area in cm^2
 L = Length in cm

If the resistivity of a material is known (see Table 1), the resistance of a conductor such as a cable or pipeline of known length and cross-sectional area can be calculated from:

$$R = \frac{\rho \times L}{A} \quad [2]$$

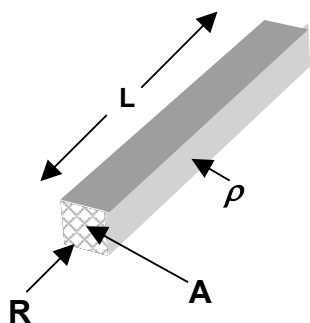


Figure 1a

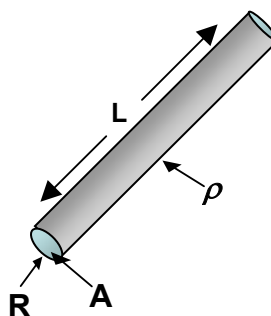


Figure 1b

Crosssectional Area:

$$A(\text{cm}^2) = h \times w$$

where: h = height (cm)

w = width (cm)

$$A(\text{cm}^2) = \pi r^2$$

where: r = radius (cm)

Electrical Schematic Diagram Symbols

Resistor



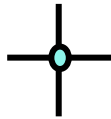
Ground



Battery



Connection



Rectifier



Switch



Diode



Electric Circuit

The *electric circuit* is the path followed by an electric current. Arrow shows direction of conventional current.

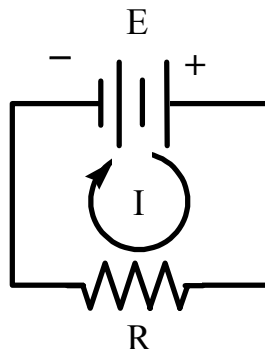


Figure 2 Basic DC Electrical Circuit

Electrical Laws

Electrical laws govern the relationships in electric circuits.

Ohm's Law

Ohm's Law is a relationship between the ratio of voltage and current to the resistance of a circuit. Ohm's Law can be expressed as follows:

where E or V = Voltage (electromotive force)
 I = Current (A)
 R = Resistance (Ω)

$$E \text{ or } V = IR \quad [3]$$

$$I = E/R \quad [4]$$

$$R = E/I \quad [5]$$

Note that the units used must be consistent: A, V and Ω . Amps and millivolts or volts and milliamps cannot be mixed.

Consider the circuit in Figure 3. A battery is connected across a known resistance.

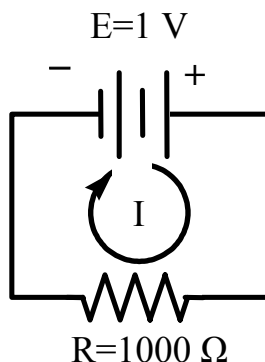


Figure .3 Current Through a Resistor

What is the current?
$$I = \frac{E}{R} = \frac{1.0 \text{ V}}{1000 \text{ } \Omega} = 0.001 \text{ A} = 1 \text{ mA}$$

Likewise, if we knew the current was 1 mA and the voltage was 1.0 V, what is the resistance?

$$R = \frac{E}{I} = \frac{1.0 \text{ V}}{0.001 \text{ A}} = 1000 \text{ } \Omega$$

Note that we had to convert 1.0 mA to 0.001 A to use Ohm's Law since the voltage is in V, not mV.

Power

Power is the energy used by an electrical device.

$$P = EI \quad [6]$$

$$P = I^2 R \quad [7]$$

where:

P = Power in watts

R = Resistance in ohms

E = Voltage in volts

I = Current in amperes

Kirchhoff's Laws

Voltage Law

The sum of the voltages in an electrical circuit is equal to zero or the sum of the source voltages around any closed loop of a circuit is equal to the sum of the voltage drops across the resistances in that loop.

For example, in Figure 4:

Source voltages = $12\text{V} + 12\text{V} = 24\text{V} = \text{IR drops } (8\text{V} + 8\text{V} + 8\text{V})$

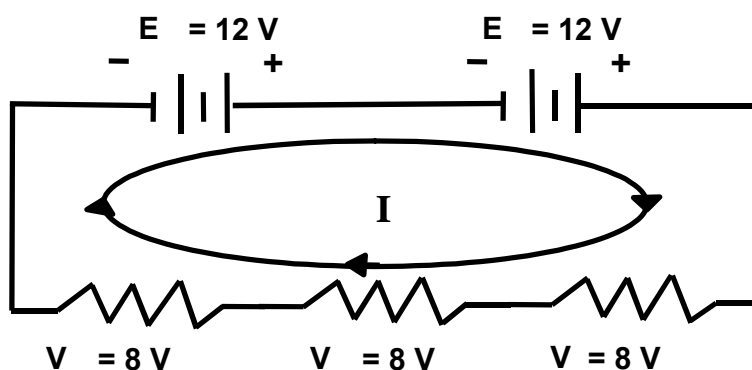


Figure 4 Kirchhoff's Voltage Law

Current Law

The sum of the current at a junction is equal to zero or as much current flows away from a point as flows toward it.

For example, in Figure 5:

Current in (6 A) = Current out ($3 + 2 + 1\text{ A}$)

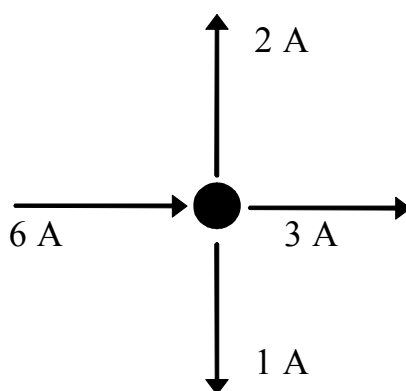


Figure 5 Kirchhoff's Current Law

Series Circuit

In a series circuit (Figure 6), the same current flows in an individual, consecutive, and continuous path from the source of voltage through the various loads and back to the source.

$$E_T = V_1 + V_2 + V_3$$

$$I_T = I_1 = I_2 = I_3$$

$$R_T = R_1 + R_2 + R_3$$

For example, consider the following circuit, where:

E_T = Total Voltage Across the Circuit

R_T = Total Resistance in the Circuit

I_T = Total Current in the Circuit

Given $E_1 = 20 \text{ V}$

$E_2 = 20 \text{ V}$

$R_1 = 5 \Omega$

$R_2 = 3 \Omega$

$R_3 = 2 \Omega$

$$R_T = 5 \Omega + 3 \Omega + 2 \Omega = 10 \Omega$$

$$I_T = \frac{E}{R} = \frac{10 \text{ V}}{10 \Omega} = 1 \text{ A}$$

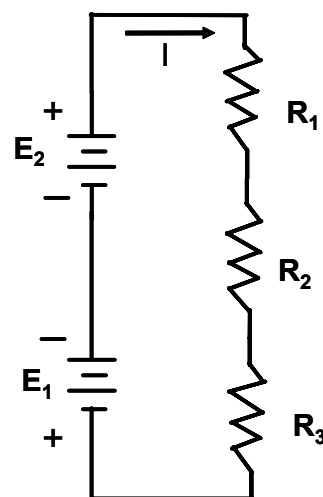


Figure 6 Series Circuit

$$\begin{array}{ll}
 I_1 = 1\text{A} & I_T R_1 = 1\text{A} \times 5\Omega = 5\text{V} \\
 I_2 = 1\text{A} & I_T R_2 = 1\text{A} \times 3\Omega = 3\text{V} \\
 I_3 = 1\text{A} & I_T R_3 = 1\text{A} \times 2\Omega = 2\text{V}
 \end{array}$$

Total IR Drop = 10V

OR

$IR_T = 1\text{A} \times 10\Omega = 10\text{V}$

$E_T = 10\text{V}$

Note that Kirchhoff's Voltage Law is fulfilled.

Parallel Circuit

In a parallel circuit (Figure 7), the current divides into a number of separate branches. Each branch may have a different resistance; thus, the value of the current in each branch may be different. Voltage drop across each element or source in the circuit is the same. If you can trace more than one path for current to flow through the circuit, you have a parallel circuit.

Galvanic anodes attached to a structure represent a parallel circuit. The same is true for impressed current anodes: the more anodes you add, the lower the resistance to the electrolyte and the more current you get.

For example, consider the following circuit:

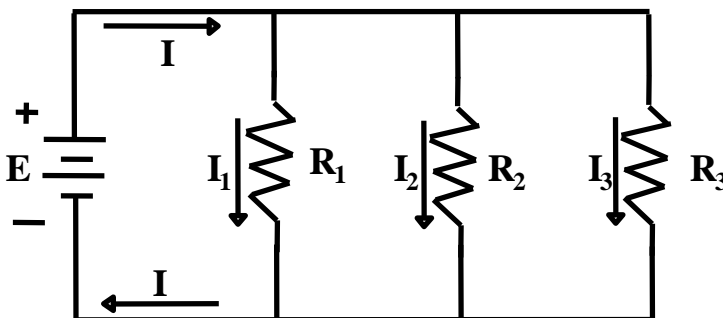


Figure 7 Parallel Circuit

$$I_T = I_1 + I_2 + I_3$$

$$E_T = I_1 R_1 = I_2 R_2 = I_3 R_3$$

$$R_T = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}}$$

$$I_1 = \frac{E_T}{R_1}$$

$$I_2 = \frac{E_T}{R_2}$$

$$I_3 = \frac{E_T}{R_3}$$

Given

$$E = 20 \text{ V}$$

$$R_1 = 5 \text{ } \Omega$$

$$R_2 = 4 \text{ } \Omega$$

$$R_3 = 2 \text{ } \Omega$$

$$IR_1 = E_T = 20\text{V} \quad I_1 = E_T/R_1 = 20\text{V}/5\Omega = 4\text{A}$$

$$IR_2 = E_T = 20\text{V} \quad I_2 = E_T/R_2 = 20\text{V}/4\Omega = 5\text{A}$$

$$IR_3 = E_T = 20\text{V} \quad I_3 = E_T/R_3 = 20\text{V}/2\Omega = 10\text{A}$$

$$I_T = 4\text{A} + 5\text{A} + 10\text{A} = 19\text{A}$$

Now consider the total circuit resistance:

$$R_T = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}} = \frac{1}{\frac{1}{5\Omega} + \frac{1}{4\Omega} + \frac{1}{2\Omega}}$$

$$R_T = \frac{1}{0.2 + 0.25 + 0.5} = \frac{1}{0.95} = 1.05 \text{ } \Omega$$

$$I_T = \frac{20 \text{ V}}{1.05 \text{ } \Omega} = 19.05 \text{ A}$$

If all the resistors in a parallel circuit are equal, the total resistance of the circuit is equal to one of the resistances divided by the number of resistors.

$$R_T = \frac{R}{N}$$

where:

R_T = Total resistance (Ω)

R = Resistance of each resistor (Ω)

N = Number of resistors

Series-Parallel Circuit

A series-parallel circuit (Figure 8) combines the elements of both a series circuit and a parallel circuit. Very complex circuits can be reduced to a circuit consisting of series-parallel elements.

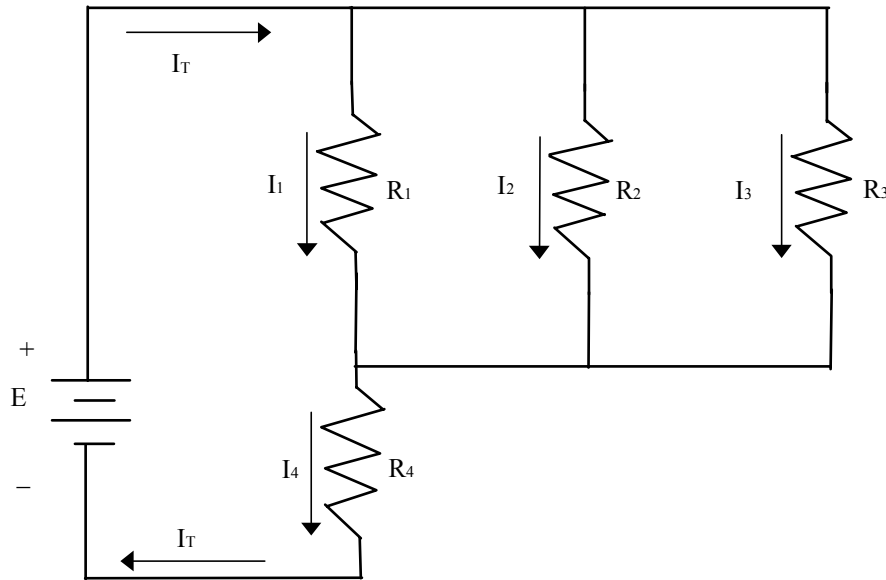


Figure 8 Series and Parallel Circuits Combined

Given $E = 20 \text{ V}$
 $R_1 = 5 \Omega$
 $R_2 = 4 \Omega$
 $R_3 = 2 \Omega$
 $R_4 = 0.95 \Omega$

First, reduce the parallel part of the circuit to a single resistance using the same formula as shown for Figure 7:

$$R_T = \frac{1}{\frac{1}{5\Omega} + \frac{1}{4\Omega} + \frac{1}{2\Omega}} = \frac{1}{0.95} = 1.05\Omega$$

We now have an equivalent series circuit of two resistors, $1.05\ \Omega$ and $0.95\ \Omega$ for a total resistance of $2.00\ \Omega$.

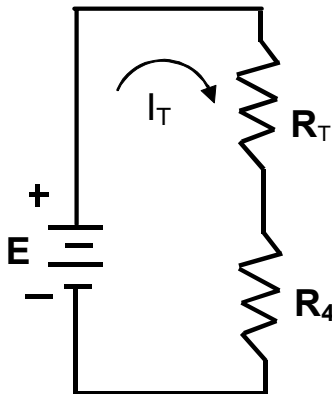


Figure 9

The total voltage, $E_T = 20\text{ V}$

Total current flow $I_T = E_T/R_T = 20\text{ V}/2.00\ \Omega = 10\text{ A}$

Next, calculate the voltage across the parallel part of the circuit. This is equal to the total voltage less the voltage drop across R_4 or $20\text{ V} - (10\text{ A} \times 0.95\ \Omega) = 10.5\text{ V}$. Calculating the currents through R_1 , R_2 , and R_3 is simply a matter of applying Ohm's Law:

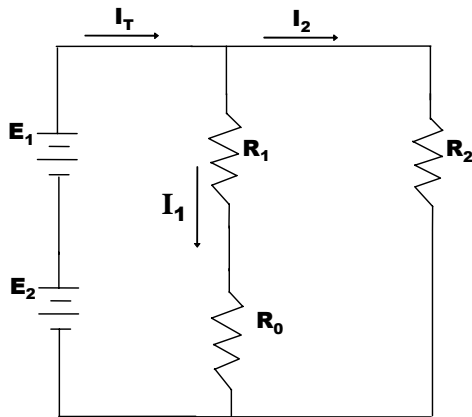
$$I_1 = 10.5\text{ V}/5\ \Omega = 2.10\text{ A}$$

$$I_2 = 10.5\text{ V}/4\ \Omega = 2.63\text{ A}$$

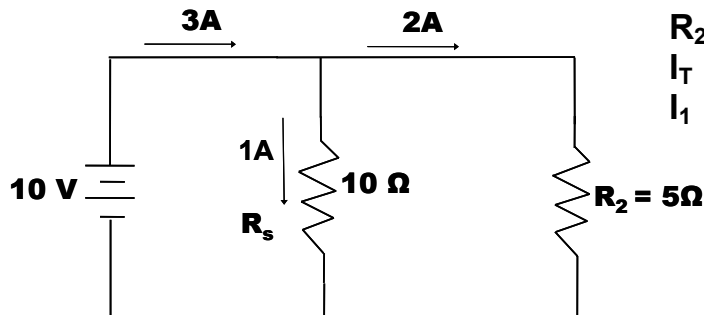
$$I_3 = 10.5\text{ V}/2\ \Omega = 5.25\text{ A}$$

$$I_T = 9.98\text{ A}$$

Note that Kirchhoff's Current Law is fulfilled also. The currents entering Points A, B, and C equal those leaving these points.

Example:

$$\begin{aligned} E_1 &= 6 \text{ V} \\ E_2 &= 4 \text{ V} \\ R_1 &= 2 \Omega \\ R_0 &= 8 \Omega \\ I_2 &= 2 \text{ A} \end{aligned}$$



$$\begin{aligned} R_2 &= ? \\ I_T &= ? \\ I_1 &= ? \text{ (current through } R_s) \end{aligned}$$

$$\begin{aligned} E_T &= E_1 + E_2 = 6 \text{ V} + 4 \text{ V} = 10 \text{ V} \\ R_s &= R_1 + R_0 = 2 \Omega + 8 \Omega = 10 \Omega \end{aligned}$$

$$I_1 = \frac{V_s}{R_s} = \frac{10 \text{ V}}{10 \Omega} = 1 \text{ A}$$

$$R_2 = \frac{V_2}{I_2} = \frac{10 \text{ V}}{2 \text{ A}} = 5 \Omega$$

Direct Current (DC)

Direct current flows in only one direction. Pure direct current is produced by a battery and appears as a straight line when viewed on an oscilloscope. See Figure 10. The circuits we have been discussing above are all based on direct current.

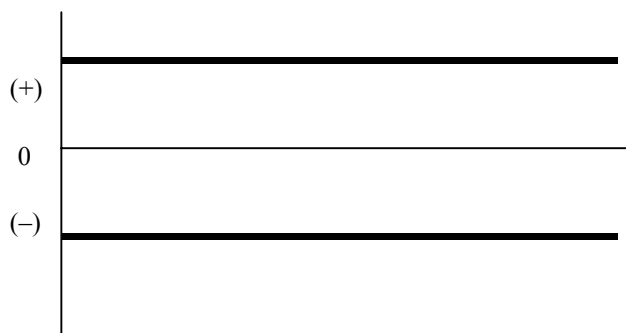


Figure 10 Pure Direct Current

Alternating Current (AC)

Alternating current, such as that which we have in our homes and buildings, reverses direction on a cyclic basis, most commonly 100 or 120 times a second. A full cycle is completed in a 50th or 60th of a second. The word hertz (hz) is used to represent a cycle, so AC is known as 50 hz or 60 hz current. Figure 11 shows a typical alternating current.

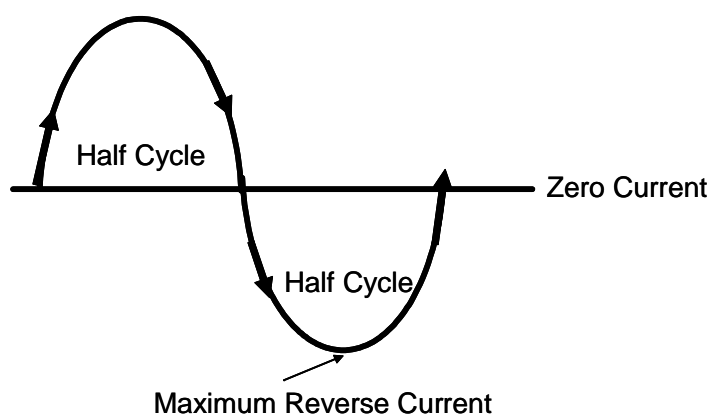


Figure 11 Typical Alternating Current

Alternating current can be turned into direct current through a rectifier. This is the function of cathodic protection rectifiers. The rectified DC still has some ripple in

it, however, so it is not the pure DC that comes from a battery. Figure 12 shows a simple rectified AC.

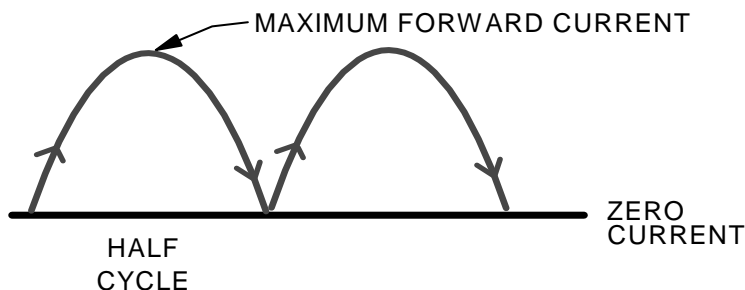


Figure 12 DC Produced by Rectifying AC

Knowledge of alternating current is important in understanding cathodic protection rectifiers. Some of the more important factors follow.

Transformers

Transformers may be used to increase or decrease voltage or to isolate an incoming voltage source from the outgoing voltage. The transformer has a laminated iron core as illustrated in Figure 13 that shows a transformer as part of a cathodic protection rectifier. There are two sets of windings on the core, the primary and the secondary. The primary winding is connected to the voltage source. The secondary winding is connected to the unit to which voltage is to be supplied.

Basic Chemistry

Corrosion is defined by NACE International as the deterioration of a material, usually a metal that results from a reaction with its environment.

Understanding corrosion and cathodic protection requires a basic knowledge of chemistry and electrochemistry. Electrochemistry is a branch of chemistry dealing with chemical changes that accompany the passage of an electric current, or a process in which a chemical reaction that produces an electric current. Pertinent terms and descriptions are given in this chapter.

Elements

All matter is made up of chemical elements. These elements are the building blocks of the physical world and are composed of atoms. As of 1998 there were 109 recognized elements, some of which have been found only as products of nuclear reactions and last for only very short periods.

Atoms

An atom consists of a nucleus and orbiting electrons. The nucleus is made up of positively charged particles called *protons* and neutral particles called *neutrons*. For any given atom, the number of protons equals the number of negatively charged electrons. Therefore, an atom has no net electrical charge. See Figure 1.

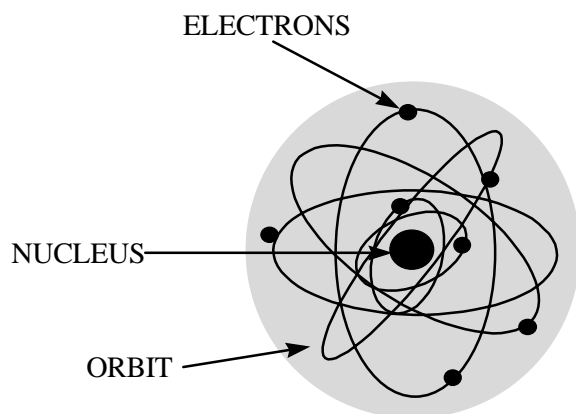


Figure 1 The Bohr Model of an Atom

Ions

Gaining or losing electrons can electrically charge atoms. Electrically charged atoms are referred to as *ions* and the charge on an atom is known as its valence state. An ion formed by the gaining of electrons is called an *anion* and is negatively charged because the number of electrons is greater than the number of protons. The loss of electrons yields a positively charged ion called a *cation*. For example, when sodium combines with chlorine an electron is transferred from sodium to chlorine, creating a positively charged sodium ion and a negatively charged chloride ion. The two ions, now of opposite charge, are electrostatically attracted to each other, forming a molecule. Ions allow for transfer of electrical charge in liquids.

Compounds (Molecules)

Molecules are composed of two or more atoms. A molecule is the smallest unit of a substance with the same specific chemical properties of that substance. For example, a single water molecule is composed of one oxygen and two hydrogen atoms as shown in Figure 2. Further splitting of this molecule would result in a substance with characteristics unlike water. The atoms of a molecule are held together by a force referred to as *chemical bonding*. It is this chemical bonding that defines many of the properties of a substance.

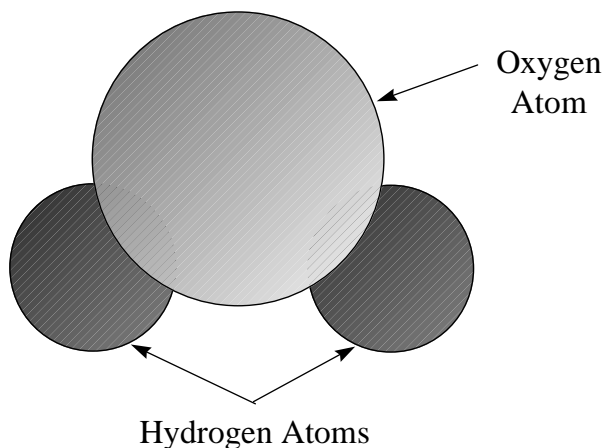


Figure 2 Water Molecule

Acidity and Alkalinity (pH)

When discussing an aqueous medium (including soil), the question often arises as to how acid or alkaline the solution is. This refers to whether there is an excess of hydrogen (H^+) or hydroxyl (OH^-) ions present.

When acids dissociate, the cation produced is the hydrogen ion, H^+ . A medium is said to be *acidic* when there is an excess of H^+ ions. The strength of an acid is a measure of the hydrogen ion concentration in an aqueous solution and is classified according to the pH scale. The definition of pH is the negative logarithm to the base 10 of the hydrogen ion concentration, or:

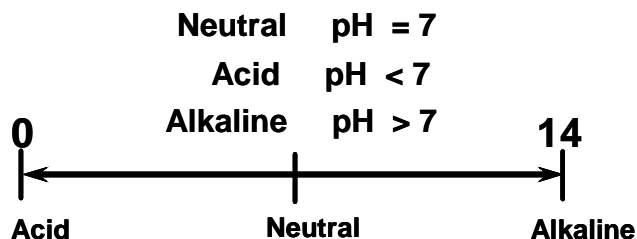
$$\text{pH} = -\log [\text{H}^+]$$

When an alkali dissociates, the anion produced is a hydroxyl ion, OH^- . A medium is said to be *alkaline* when an excess OH^- (hydroxyl) ions are present.

This concept is better understood if we look at pure water, H_2O . Pure water will ionize into equal parts of hydrogen ions (H^+) and hydroxyl ions (OH^-). The ionization constant for water is the square root of 10^{-14} . That equals 10^{-7} . This is the definition of a negative logarithm. Since water ionizes into equal parts of hydrogen and hydroxyl ions, 7 represents a neutral solution.

The pH scale is illustrated in Figure 3. The neutral point is 7. Acid solutions have a pH below 7 and alkaline, or basic, solutions have a pH above 7. Since the pH scale is logarithmic, for each unit of pH the environment

becomes ten times more acid or alkaline. A medium with a pH of 6, for example, is ten times more acid than one having a pH of 7.



$$\text{pH} = -\log [\text{H}^+]$$

Figure 3 Illustration of Acid and Alkaline pH

An understanding of pH is important in corrosion and cathodic protection work. For many metals, the rate of corrosion increases appreciably below a pH of about 4. Between 4 and 8 corrosion rate is fairly independent of pH. Above 8, the environment becomes passive and corrosion rates tend to decrease. This is shown in Figure 4, which is typical of the behavior of steel.

The corrosion rate of aluminum and lead, on the other hand, tends to increase in environments above a pH of about 8. This is because the protective oxide film on the surface of these metals is dissolved in most strong acids and alkalis and the metals corrode. Metals that corrode under low and high pH levels are termed *amphoteric* metals. Figure 2.4 illustrates this phenomenon.

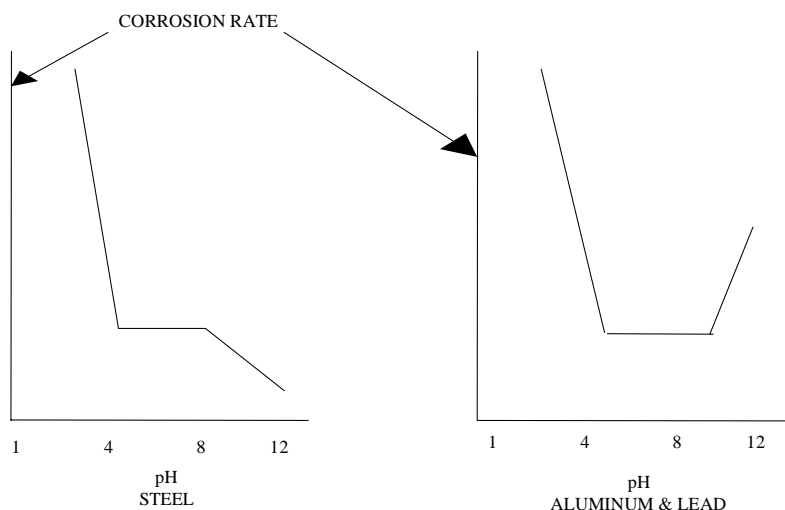


Figure 4 Effect of pH on the Rate of Corrosion

An understanding of the effect of pH is also important in the application of cathodic protection. The pH of the environment around the cathode (the protected structure) becomes more alkaline due to the production of hydroxyl ions or removal of hydrogen ions. This is important when working with amphoteric metals, as the corrosion of these metals can actually be accelerated under excessive cathodic protection due to the rise in pH around the structure.

Basic Electrochemistry

Electrochemistry is the division of chemistry that deals with the transfer of electric charge in chemical reactions. These chemical reactions are electrochemical reactions. One branch deals with solid state reactions that take place in semiconductors such as transistors and diodes. Corrosion and cathodic protection pertain to the branch of electrochemistry concerned with charge transfer in aqueous or other liquid environments.

Oxidation and Reduction

Oxidation

Oxidation is the term applied to the loss of one or more electrons from an atom or molecule, which then forms a positively charged ion. An oxidation reaction occurs any time electrons are given up by an atom or molecule. The atom or molecule decreases in negative charge.

For example, when a neutral iron atom (Fe) oxidizes, it may lose two or three electrons, producing positively charged iron ions (Fe^{++} or Fe^{+++}), as shown in Figure 5.

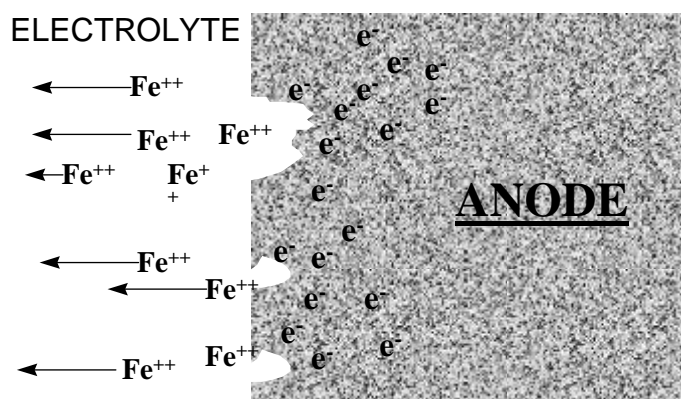
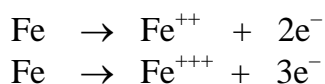


Figure 5 Anodic Process (half reaction)

The electrode or metallic site where oxidation occurs is called an *anode*.

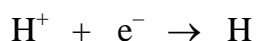
Note: The term oxidation is not necessarily associated with oxygen.

Reduction

Reduction is the term applied to the gain of one or more electrons to an atom or molecule, which then forms a negatively charged ion or neutral element.

A reduction reaction occurs any time **that** electrons are gained by an atom or molecule. The atom or molecule increases in negative charge.

For example, when a hydrogen ion (H^+) is reduced, it gains one electron, producing a neutral hydrogen atom (H).



The electrode or metallic site where reduction occurs is called a *cathode*. The process appears in Figure 6.

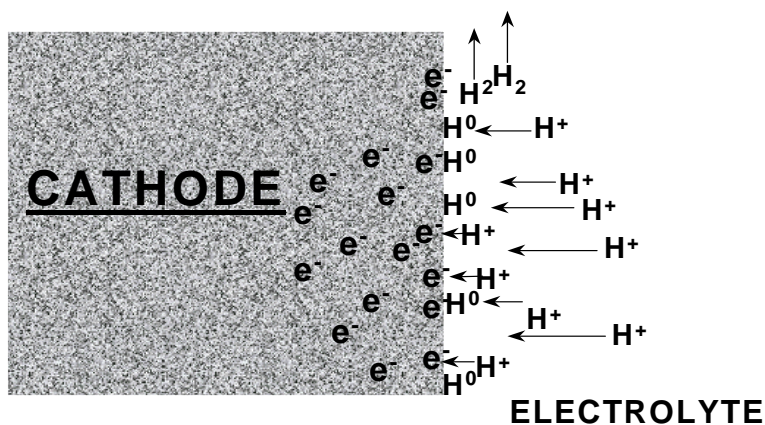
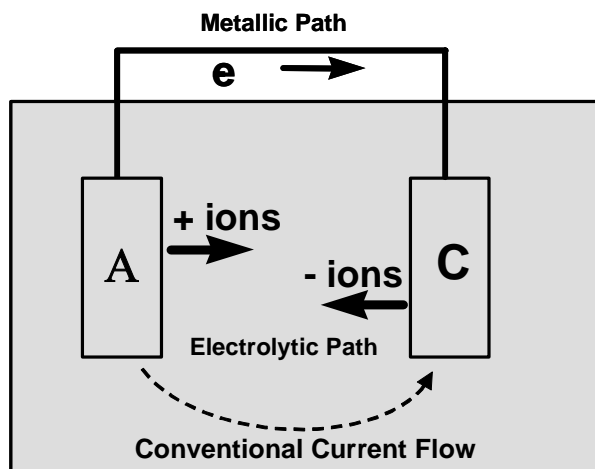


Figure 6 Cathodic Process (half reaction)

Electrochemical Circuits

The basic electrochemical corrosion cell is illustrated in Figure 7. The various parts of the basic cell are discussed following the figure.



*Figure 7 Basic Corrosion Cell –
An Electrochemical Circuit*

Electrolyte

The *electrolyte* is an ionized solution capable of conducting electricity.

Ionization

In addition to ions that may be produced in oxidation and reduction reactions, ions may be present in the electrolyte due to dissociation of ionized molecules. Cations are positively charged ions and anions are negatively charged ions). These ions are current-carrying charges. Therefore, electrolytes with higher ionization have greater conductivity.

Corrosion Cell

Corrosion is an electrochemical process involving the flow of electrons and ions. Metal loss (corrosion) occurs at the anode. No metal loss occurs at the cathode (the cathode is protected).

Electrochemical corrosion involves the transfer of electrons across metal/electrolyte interfaces. Corrosion occurs within a corrosion cell. A corrosion cell consists of four parts as illustrated in Figure 8.

- Anode
- Cathode
- Electrolyte
- Metallic Path

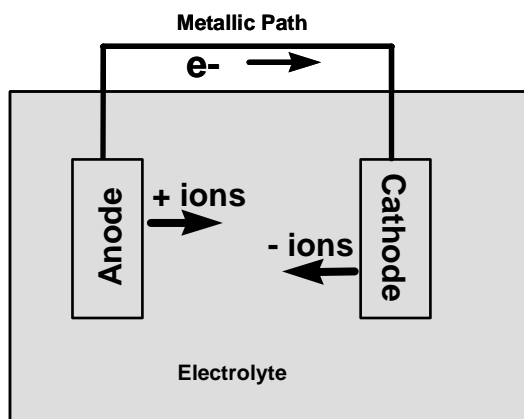


Figure 8 Corrosion Cell

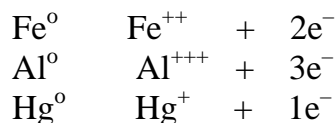
Anode Reactions

The chemical reaction that occurs at the anode, the anodic reaction, is an oxidation reaction. Corrosion is the result of the oxidation reaction in a corrosion cell. Oxidation is the loss of electrons as shown in the following reaction:



where n is the number of electrons involved.

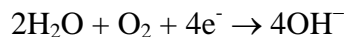
Other anode reactions:



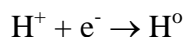
Cathode Reactions

The chemical reaction that occurs at the cathode, the cathodic reaction, is a reduction reaction. Reduction is the gain of electrons. The actual cathodic reaction that occurs will depend on the electrolyte. The following reactions are the two most common reduction reactions that occur at the surface of the cathode.

Oxygen Reduction—more common in neutral environments.



Hydrogen Ion Reduction—more common in acidic environments



Corrosion never occurs at the cathode of a corrosion cell.

The anode and the cathode can be on different metals or on the same metal as shown in Figure 9.

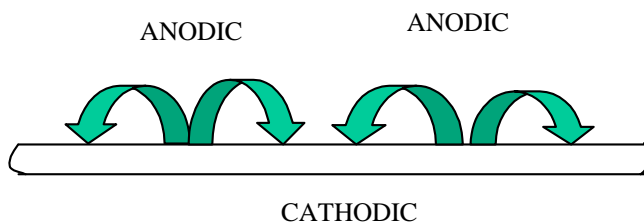


Figure 9 Typical Local Action Corrosion Cells on a Structure

External Circuit

The *external circuit* refers to those parts of an electrochemical circuit in which charge movement is electronic; that is, it involves the movement of electrons.

The electric current produced by oxidation and reduction flows through the electronic path by means of electron movement. The electrons produced in the oxidation reaction flow from the anode to the cathode to provide electrons for the reduction reaction to occur. This is shown in Figure 10.

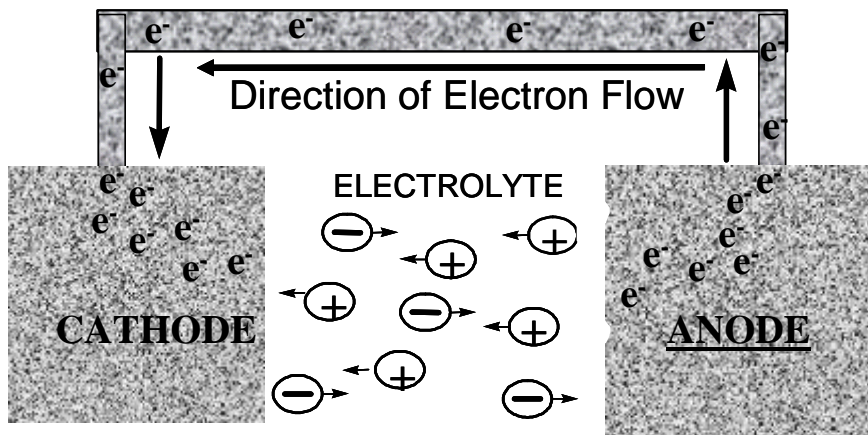


Figure 10 Electron and Ion Flow

Charge Transfer in the Electrolyte

Movement of charged ions is the mechanism for charge transfer through an electrolyte as opposed to the flow of electrons in a solid metal conductor. Positively charged ions (cations) move away from the anode and toward the cathode. (Note: the ions do not plate out on the cathode.) On the other hand, negatively charged ions (anions) move toward the anode and away from the cathode. This charge transfer is called *electrolytic current flow*. This charge transfer is shown in Figure 10.

Ions are relatively heavy and slow moving. Consequently, electrolytes have much higher resistivities than metals. This causes a phenomenon called polarization.

Meter Operation

General

The classification of a meter depends on the inner workings and the display of the meter. The inner workings of a meter may be either electromechanical movement or electronic. The display may be either analog or digital. Earlier instruments were constructed using an electromechanical movement with an analog display and are referred to as *analog meters*. These instruments have a needle that rotates across the meter face and indicates the reading on a scale.

Today, most instruments are electronic with digital displays and are referred to as *digital meters*. Hybrid meters that are electronic with analog displays (electronic amplifiers driving an electromechanical coil) are sometimes referred to as *electronic meters* (see Figure 1.).

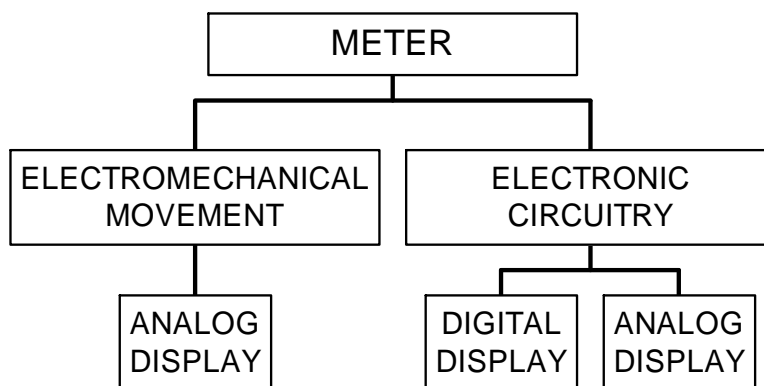


Figure 1 Meter Operation

Analog Meters

Basic Meter Movement

The basic movement of an analog meter is a stationary permanent magnet/moving coil system called a *D'Arsonval movement*. This is shown in Figure 2. The needle provides a continuous representation of the measurement, called an *analog* of the measurement value.

The D'Arsonval meter responds to a current flow through the moving coil. Electrical current is converted into a mechanical force, as indicated in the following steps:

1. Current from the external circuit flows through the coil and creates a magnetic field.
2. The coil rotates due to the reaction of its magnetic field with the magnetic field of the permanent magnet.
3. As the coil rotates, it works against a mechanical spring, causing tension in the spring.
4. The pointer comes to rest along the calibrated scale based on the balance in forces between the moving magnetic coil and the spring tension.
5. The reading on the scale represents the current flow through the coil from the external circuit. Note that the energy needed to operate the meter comes from the circuit itself.

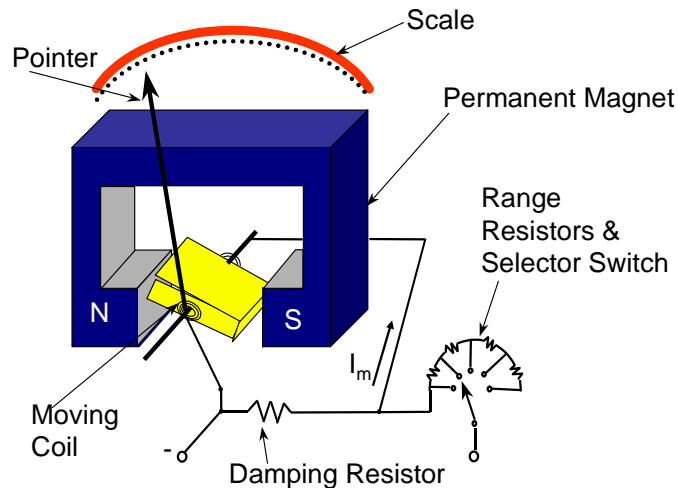


Figure 2 D'Arsonval Movement (Voltmeter)

Of the total current required to cause full-scale deflection, part of the current will flow through the moving coil and part through the damping resistor. The damping resistor is connected in parallel with

the moving coil; its function is to reduce needle overswing and permit the needle to come to rest within a reasonable period of time.

The coil is delicate and can be destroyed easily if large currents flow through it; therefore, resistors are placed either in series or parallel to the meter movement to control the maximum current flow through the meter coil.

Whether an analog meter is used to measure voltage, current, or resistance, each of these measurements depend on the measurement of current flow. The meter measures current directly, and, by knowing one of the other variables, the third variable can be calculated by using Ohm's Law.

To obtain an upscale reading (needle moving to the right) current must enter the meter on the positive terminal. Remembering this will enable you to determine the direction of current flow in the circuit with which you are working.

Also, when using an analog meter, the reference electrode is connected to the positive terminal to obtain an upscale reading.

Voltmeters

Because the D'Arsonval meter responds to current flow through the coil, the current magnitude resulting in full-scale deflection of the meter can be determined. Also, the series resistance of the meter coil is known. The meter can be used to determine voltage by using Ohm's Law. The full-scale voltage is simply the full-scale current times the coil resistance. This is the smallest full-scale voltage range possible with the meter. Larger full-scale voltage ranges can be made available by switching resistors in series with the moving coil, which reduces the magnitude of voltage drop directly across the coil.

For low-voltage ranges, the circuit resistance becomes more sensitive and external resistances such as those associated with test leads and reference electrode-to-electrolyte contact may cause an error in the reading.

WARNING – DO NOT TOUCH THE METAL PARTS OF THE TEST WIRES WHEN TAKING VOLTAGE READINGS.

Ammeters

If the meter is used as an ammeter, resistors are placed parallel to the moving coil to shunt a significant portion of the total current around the moving coil. The position of the range switch determines the value of the shunt resistance. The higher the current to be measured, the smaller the shunt resistor must be to allow greater portions of the current to bypass the coil.

Ohmmeters

If the current is measured and the driving voltage is known, the resistance of the circuit can be calculated by Ohm's Law. An ohmmeter measures the current flow caused by a known voltage source and indicates resistance on the scale or readout.

Ohmmeters find limited use in corrosion work. They can be useful for checking circuit continuity and for other testing in rectifiers or resistor panels, but they are not suitable for testing resistance between structures in an electrolyte (e.g., across an isolation joint, or casing to pipe). There are two reasons for this. First, when two structures are electrically isolated from each other by a fitting, there is a parallel resistance through the electrolyte. The ohmmeter cannot distinguish between the resistance of the fitting and the resistance through the electrolyte. More important, however, is the fact that there is nearly always a voltage difference between two isolated structures. This voltage affects the total voltage of the measuring circuit and creates appreciable errors. A high resistance may be indicated with the leads connected one way and a low resistance with the leads reversed.

<p>WARNING – DO NOT TOUCH THE METAL PARTS OF THE TEST WIRES WHEN TAKING VOLTAGE READINGS.</p>
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Digital Meters

Basis of Operation

A digital meter is based on integrated microcircuit technology. The analog input is sampled over a specific period of time. The average input over this time is then converted to a digital value, a coded number, using an analog-to-digital (A-to-D) converter. For a digital multimeter (DMM), all measurements are converted to DC volts prior to the analog-to-digital conversion. The displayed value is not continuous but a sample of the input value measurements. However, the measurement is taken several times per second. The measured value is displayed as discrete digits; the digits do not require operator interpretation as the analog display does. If a voltage is changing, the numbers are also changing, and it may be difficult to read a specific value from the fluctuating members. Therefore, in areas with stray current, a digital meter may not be as useful as an analog meter.

Meter Hook Up

When current enters the meter on the positive terminal, a positive sign (+) is displayed. A negative sign (–) is displayed when current enters the meter on the negative terminal. Remembering this will enable you to determine the direction of current flow in the circuit with which you are working.

Also, when using a digital meter, the reference electrode is connected to the negative terminal to obtain the proper polarity reading.

NACE GLOSSARY OF CORROSION-RELATED TERMS



ABRASIVE

Small particles of material that are propelled at high velocity to impact a surface during abrasive blast cleaning.

ABRASIVE BLAST CLEANING

Cleaning and roughening of a surface produced by the high-velocity impact of an abrasive that is propelled by the discharge of pressurized fluid from a blast nozzle or by a mechanical device such as a centrifugal blasting wheel. (Also referred to as *Abrasive Blasting*.)

ACCELERATOR

A chemical substance that increases the rate at which a chemical reaction (e.g., curing) would otherwise occur.

ACRYLIC

Type of resin polymerized from acrylic acid, methacrylic acid, esters of these acids, or acrylonitrile.

ACTIVATOR

A chemical substance that initiates and accelerates a chemical reaction (e.g., curing). Heat and radiation may also serve as activators for some chemical reactions.

ACTIVE

(1) The negative direction of electrode potential. (2) A state of a metal that is corroding without significant influence of reaction product.

AERATION CELL

[See *Differential Aeration Cell*.]

AIR DRYING

Process by which an applied wet coat converts to a dry coating film by evaporation of solvent or reaction with oxygen as a result of simple exposure to air without intentional addition of heat or a curing agent.

AIRLESS SPRAYING

Process of spraying coating liquids using hydraulic pressure, not air pressure, to atomize.

ALKYD

Type of resin formed by the reaction of polyhydric alcohols and polybasic acids, part of which is derived from saturated or unsaturated oils or fats.

ALLIGATORING

Pronounced wide cracking over the surface of a coating, which has the appearance of alligator hide.

AMPHOTERIC METAL

A metal that is susceptible to corrosion in both acid and alkaline environments.

ANAEROBIC

Free of air or uncombined oxygen.

ANION

A negatively charged ion that migrates through the electrolyte toward the anode under the influence of a potential gradient.

ANODE

The electrode of an electrochemical cell at which oxidation occurs. Electrons flow away from the anode in the

external circuit. Corrosion usually occurs and metal ions enter the solution at the anode.

ANODE CAP

An electrical insulating material placed over the end of the anode at the lead wire connection.

ANODE CORROSION EFFICIENCY

The ratio of the actual corrosion (mass loss) of an anode to the theoretical corrosion (mass loss) calculated from the quantity of electricity that has passed between the anode and cathode using Faraday's law.

ANODIC INHIBITOR

A chemical substance that prevents or reduces the rate of the anodic or oxidation reaction.

ANODIC POLARIZATION

The change of the electrode potential in the noble (positive) direction caused by current across the electrode/electrolyte interface. [See *Polarization*.]

ANODIC PROTECTION

Polarization to a more oxidizing potential to achieve a reduced corrosion rate by the promotion of passivity.

ANODIZING

Oxide coating formed on a metal surface (generally aluminum) by an electrolytic process.

ANOLYTE

The electrolyte adjacent to the anode of an electrochemical cell.

ANTIFOULING

Preventing fouling. [See *Fouling*.]

NACE GLOSSARY OF CORROSION-RELATED TERMS

ATTENUATION

Electrical losses in a conductor caused by current flow in the conductor.

AUGER ELECTRON SPECTROSCOPY

Analytical technique in which the sample surface is irradiated with low-energy electrons and the energy spectrum of electrons emitted from the surface is measured.

AUSTENITIC STEEL

A steel whose microstructure at room temperature consists predominantly of austenite.

AUXILIARY ELECTRODE

An electrode, usually made from a noncorroding material, which is commonly used in polarization studies to pass current to or from a test electrode.



BACKFILL

Material placed in a hole to fill the space around the anodes, vent pipe, and buried components of a cathodic protection system.

BARRIER COATING

(1) A coating that has a high resistance to permeation of liquids and/or gases. (2) A coating that is applied over a previously coated surface to prevent damage to the underlying coating during subsequent handling

BEACH MARKS

The characteristic markings on the fracture surfaces produced by fatigue crack propagation

(also known as *clamshell marks*, *conchoidal marks*, and *arrest marks*).

BETA CURVE

A plot of dynamic (fluctuating) interference current or related proportional voltage (ordinate) versus the corresponding structure-to-electrolyte potentials at a selected location on the affected structure (abscissa).

BINDER

The nonvolatile portion of the vehicle of a formulated coating material.

BITUMINOUS COATING

An asphalt or coal-tar compound used to provide a protective coating for a surface.

BLAST ANGLE

(1) The angle of the blast nozzle with reference to the surface during abrasive blast cleaning. (2) The angle of the abrasive particles propelled from a centrifugal blasting wheel with reference to the surface being abrasive blast cleaned.

BLOWDOWN

(1) Injection of air or water under high pressure through a tube to the anode area for the purpose of purging the annular space and possibly correcting high resistance caused by gas blockage. (2) In conjunction with boilers or cooling towers, the process of discharging a significant portion of the aqueous solution in order to remove accumulated salts, deposits, and other impurities.

BLUSHING

Whitening and loss of gloss of a coating, usually organic, caused

by moisture (also known as *blooming*).

BRACELET ANODES

Galvanic anodes with geometry suitable for direct attachment around the circumference of a pipeline. These may be half-shell bracelets consisting of two semi-circular sections or segmented bracelets consisting of a large number of individual anodes.

BRITTLE FRACTURE

Fracture with little or no plastic deformation.

BRUSH-OFF BLAST CLEANED SURFACE

A brush-off blast cleaned surface, when viewed without magnification, shall be free of all visible oil, grease, dirt, dust, loose mill scale, loose rust, and loose coating. Tightly adherent mill scale, rust, and coating may remain on the surface. Mill scale, rust, and coating are considered tightly adherent if they cannot be removed by lifting with a dull putty knife. [See NACE No. 4/SSPC-SP 7.]



CALCAREOUS COATING

A layer consisting of calcium carbonate and other salts deposited on the surface. When the surface is cathodically polarized as in cathodic protection, this layer is the result of the increased pH adjacent to the protected surface.

CALCAREOUS DEPOSIT

[See *Calcareous Coating*.]

NACE GLOSSARY OF CORROSION-RELATED TERMS

CASE HARDENING

Hardening a ferrous alloy so that the outer portion, or case, is made substantially harder than the inner portion, or core. Typical processes are carburizing, cyaniding, carbonitriding, nitriding, induction hardening, and flame hardening.

CASEIN PAINT

Water-thinned paint with vehicle derived from milk.

CATALYST

A chemical substance, usually present in small amounts relative to the reactants, that increases the rate at which a chemical reaction (e.g., curing) would otherwise occur, but is not consumed in the reaction.

CATHODE

The electrode of an electrochemical cell at which reduction is the principal reaction. Electrons flow toward the cathode in the external circuit.

CATHODIC CORROSION

Corrosion resulting from a cathodic condition of a structure, usually caused by the reaction of an amphoteric metal with the alkaline products of electrolysis.

CATHODIC DISBONDMENT

The destruction of adhesion between a coating and the coated surface caused by products of a cathodic reaction.

CATHODIC INHIBITOR

A chemical substance that prevents or reduces the rate of the cathodic or reduction reaction.

CATHODIC POLARIZATION

The change of the electrode potential in the active (negative) direction caused by current across the electrode/electrolyte interface. [See *Polarization*.]

CATHODIC PROTECTION

A technique to reduce the corrosion of a metal surface by making that surface the cathode of an electrochemical cell.

CATHOLYTE

The electrolyte adjacent to the cathode of an electrochemical cell.

CATION

A positively charged ion that migrates through the electrolyte toward the cathode under the influence of a potential gradient.

CAVITATION

The formation and rapid collapse of cavities or bubbles within a liquid which often results in damage to a material at the solid/liquid interface under conditions of severe turbulent flow.

CELL

[See *Electrochemical Cell*.]

CEMENTATION

The introduction of one or more elements into the surface layer of a metal by diffusion at high temperature. (Examples of cementation include carburizing [introduction of carbon], nitriding [introduction of nitrogen], and chromizing [introduction of chromium].)

CHALKING

The development of loose, removable powder (pigment) at

the surface of an organic coating, usually caused by weathering.

CHECKING

The development of slight breaks in a coating which do not penetrate to the underlying surface.

CHEMICAL CONVERSION COATING

An adherent reaction product layer on a metal surface formed by reaction with a suitable chemical to provide greater corrosion resistance to the metal and increase adhesion of coatings applied to the metal. (Example is an iron phosphate coating on steel, developed by reaction with phosphoric acid.)

CHEVRON PATTERN

A V-shaped pattern on a fatigue or brittle-fracture surface. The pattern can also be one of straight radial lines on cylindrical specimens.

CHLORIDE STRESS CORROSION CRACKING

Cracking of a metal under the combined action of tensile stress and corrosion in the presence of chlorides and an electrolyte (usually water).

COAT

One layer of a coating applied to a surface in a single continuous application to form a uniform film when dry.

COATING

A liquid, liquefiable, or mastic composition that, after application to a surface, is converted into a solid protective, decorative, or functional adherent film.

NACE GLOSSARY OF CORROSION-RELATED TERMS

COATING SYSTEM

The complete number and types of coats applied to a substrate in a predetermined order. (When used in a broader sense, surface preparation, pretreatments, dry film thickness, and manner of application are included.)

COLD LAP

(1) Discontinuity caused by solidification of the meniscus of a partially cast anode as a result of interrupted flow of the casting stream. The solidified meniscus is covered with metal when the flow resumes. Cold laps can occur along the length of an anode. (2) A protective film consisting of one or more coats, applied in a predetermined order by prescribed methods to an as-specified dry film thickness, including any reinforcing material that may be specified.

COLD SHUT

Horizontal surface discontinuity caused by solidification of a portion of a meniscus during the progressive filling of a mold, which is later covered with more solidifying metal as the molten metal level rises. Cold shuts generally occur at corners remote from the point of pour.

COMMERCIAL BLAST CLEANED SURFACE

A commercial blast cleaned surface, when viewed without magnification, shall be free of all visible oil, grease, dust, dirt, mill scale, rust, coating, oxides, corrosion products, and other foreign matter. Random staining shall be limited to no more than 33 percent of each unit area (approximately 58 cm² [9.0 in.²]) of surface and may consist of light shadows, slight streaks, or

minor discolorations caused by stains of rust, stains of mill scale, or stains of previously applied coating. [See NACE No. 3/SSPC-SP 6.]

CONCENTRATION CELL

An electrochemical cell, the electromotive force of which is caused by a difference in concentration of some component in the electrolyte. (This difference leads to the formation of discrete cathodic and anodic regions.)

CONCENTRATION POLARIZATION

That portion of polarization of a cell produced by concentration changes resulting from passage of current through the electrolyte.

CONDUCTIVE COATING

(1) A coating that conducts electricity. (2) An electrically conductive, mastic-like material used as an impressed current anode on reinforced concrete surfaces.

CONDUCTIVE CONCRETE

A highly conductive cement-based mixture containing coarse and fine coke and other material used as an impressed current anode on reinforced concrete surfaces.

CONDUCTIVITY

(1) A measure of the ability of a material to conduct an electric charge. It is the reciprocal of resistivity. (2) The current transferred across a material (e.g., coating) per unit potential gradient.

CONTACT CORROSION

[See *Galvanic Corrosion*.]

CONTINUITY BOND

A connection, usually metallic, that provides electrical continuity between structures that can conduct electricity.

CONTINUOUS ANODE

A single anode with no electrical discontinuities.

CONVERSION COATING

[See *Chemical Conversion Coating*.]

CORROSION

The deterioration of a material, usually a metal, that results from a reaction with its environment.

CORROSION FATIGUE

Fatigue-type cracking of metal caused by repeated or fluctuating stresses in a corrosive environment characterized by shorter life than would be encountered as a result of either the repeated or fluctuating stress alone or the corrosive environment alone.

CORROSION INHIBITOR

A chemical substance or combination of substances that, when present in the environment, prevents or reduces corrosion.

CORROSION POTENTIAL (E_{corr})

The potential of a corroding surface in an electrolyte relative to a reference electrode under open-circuit conditions (also known as *rest potential*, *open-circuit potential*, or *freely corroding potential*).

NACE GLOSSARY OF CORROSION-RELATED TERMS

CORROSION RATE

The rate at which corrosion proceeds.

CORROSION RESISTANCE

Ability of a material, usually a metal, to withstand corrosion in a given system.

CORROSIVENESS

The tendency of an environment to cause corrosion.

COUNTER ELECTRODE

[See *Auxiliary Electrode*.]

COUNTERPOISE

A conductor or system of conductors arranged beneath a power line, located on, above, or most frequently, below the surface of the earth and connected to the footings of the towers or poles supporting the power line.

COUPLE

[See *Galvanic Couple*.]

CRACKING (OF COATING)

Breaks in a coating that extend through to the substrate.

CRAZING

A network of checks or cracks appearing on the surface of a coating.

CREEP

Time-dependent strain occurring under stress.

CREVICE CORROSION

Localized corrosion of a metal surface at, or immediately adjacent to, an area that is shielded from full exposure to the

environment because of close proximity of the metal to the surface of another material.

CRITICAL HUMIDITY

The relative humidity above which the atmospheric corrosion rate of some metals increases sharply.

CRITICAL PITTING POTENTIAL (E_p , E_{pp})

The lowest value of oxidizing potential (voltage) at which pits nucleate and grow. The value depends on the test method used.

CURING

Chemical process of developing the intended properties of a coating or other material (e.g., resin) over a period of time.

CURING AGENT

A chemical substance used for curing a coating or other material (e.g., resin). [Also referred to as *Hardener*.]

CURRENT

(1) A flow of electric charge. (2) The amount of electric charge flowing past a specified circuit point per unit time, measured in the direction of net transport of positive charges. (In a metallic conductor, this is the opposite direction of the electron flow.)

CURRENT DENSITY

The current to or from a unit area of an electrode surface.

CURRENT EFFICIENCY

The ratio of the electrochemical equivalent current density for a specific reaction to the total applied current density.



DC DECOUPLING DEVICE

A device used in electrical circuits that allows the flow of alternating current (AC) in both directions and stops or substantially reduces the flow of direct current (DC).

DEALLOYING

The selective corrosion of one or more components of a solid solution alloy (also known as *parting* or *selective dissolution*).

DECOMPOSITION POTENTIAL

The potential (voltage) on a metal surface necessary to decompose the electrolyte of an electrochemical cell or a component thereof.

DECOMPOSITION VOLTAGE

[See *Decomposition Potential*.]

DEEP GROUNDBED

One or more anodes installed vertically at a nominal depth of 15 m (50 ft) or more below the earth's surface in a drilled hole for the purpose of supplying cathodic protection.

DEPOLARIZATION

The removal of factors resisting the current in an electrochemical cell.

DEPOSIT ATTACK

Corrosion occurring under or around a discontinuous deposit on a metallic surface (also known as *poultice corrosion*).

NACE GLOSSARY OF CORROSION-RELATED TERMS

DEZINCIFICATION

A corrosion phenomenon resulting in the selective removal of zinc from copper-zinc alloys. (This phenomenon is one of the more common forms of dealloying.)

DIELECTRIC COATING

A coating that does not conduct electricity.

DIELECTRIC SHIELD

An electrically nonconductive material, such as a coating, sheet or pipe, that is placed between an anode and an adjacent cathode, usually on the cathode, to improve current distribution in a cathodic protection system.

DIFFERENTIAL AERATION CELL

An electrochemical cell, the electromotive force of which is due to a difference in air (oxygen) concentration at one electrode as compared with that at another electrode of the same material.

DIFFUSION-LIMITED CURRENT DENSITY

The current density that corresponds to the maximum transfer rate that a particular species can sustain because of the limitation of diffusion (often referred to as *limiting current density*).

DISBONDMENT

The loss of adhesion between a coating and the substrate.

DISSIMILAR METALS

Different metals that could form an anode-cathode relationship in an electrolyte when connected by

a metallic path.

DOUBLE LAYER

The interface between an electrode or a suspended particle and an electrolyte created by charge-charge interaction leading to an alignment of oppositely charged ions at the surface of the electrode or particle. The simplest model is represented by a parallel plate condenser.

DOUBLER PLATE

An additional plate or thickness of steel used to provide extra strength at the point of anode attachment to an offshore platform.

DRAINAGE

Conduction of electric current from an underground or submerged metallic structure by means of a metallic conductor.

DRIVING POTENTIAL

Difference in potential between the anode and the steel structure.

DRYING OIL

An oil capable of conversion from a liquid to a solid by slow reaction with oxygen in the air.



ELASTIC DEFORMATION

Changes of dimensions of a material upon the application of a stress within the elastic range. Following the release of an elastic stress, the material returns to its original dimensions without any permanent deformation.

ELASTIC LIMIT

The maximum stress to which a material may be subjected without retention of any permanent deformation after the stress is removed.

ELASTICITY

The property of a material that allows it to recover its original dimensions following deformation by a stress below its elastic limit.

ELECTRICAL INTERFERENCE

Any electrical disturbance on a metallic structure in contact with an electrolyte caused by stray current(s).

ELECTRICAL ISOLATION

The condition of being electrically separated from other metallic structures or the environment.

ELECTRO-OSMOSIS

The migration of water through a semipermeable membrane as a result of a potential difference caused by the flow of electric charge through the membrane.

ELECTROCHEMICAL CELL

A system consisting of an anode and a cathode immersed in an electrolyte so as to create an electrical circuit. The anode and cathode may be different metals or dissimilar areas on the same metal surface.

ELECTROCHEMICAL EQUIVALENT

The mass of an element or group of elements oxidized or reduced at 100% efficiency by the passage of a unit quantity of electricity.

NACE GLOSSARY OF CORROSION-RELATED TERMS

ELECTROCHEMICAL POTENTIAL

The partial derivative of the total electrochemical free energy of a constituent with respect to the number of moles of this constituent where all other factors are kept constant. It is analogous to the chemical potential of a constituent except that it includes the electrical as well as chemical contributions to the free energy.

ELECTRODE

A conductor used to establish contact with an electrolyte and through which current is transferred to or from an electrolyte.

ELECTRODE POTENTIAL

The potential of an electrode in an electrolyte as measured against a reference electrode. (The electrode potential does not include any resistance losses in potential in either the electrolyte or the external circuit. It represents the reversible work to move a unit of charge from the electrode surface through the electrolyte to the reference electrode.)

ELECTROKINETIC POTENTIAL

A potential difference in a solution caused by residual, unbalanced charge distribution in the adjoining solution, producing a double layer. The electrokinetic potential is different from the electrode potential in that it occurs exclusively in the solution phase. This potential represents the reversible work necessary to bring a unit charge from infinity in the solution up to the interface in question but not through the interface (also known

as *zeta potential*).

ELECTROLYTE

A chemical substance containing ions that migrate in an electric field.

ELECTROLYTIC CLEANING

A process for removing soil, scale, or corrosion products from a metal surface by subjecting the metal as an electrode to an electric current in an electrolytic bath.

ELECTROMOTIVE FORCE SERIES

A list of elements arranged according to their standard electrode potentials, the sign being positive for elements whose potentials are cathodic to hydrogen and negative for those anodic to hydrogen.

ELLIPSOMETRY

An optical analytical technique employing plane-polarized light to study films.

EMBRITTLEMENT

Loss of ductility of a material resulting from a chemical or physical change.

EMF SERIES

[See *Electromotive Force Series*.]

ENAMEL

(1) A paint that dries to a hard, glossy surface. (2) A coating that is characterized by an ability to form a smooth, durable film.

END EFFECT

The more rapid loss of anode material at the end of an anode, compared with other surfaces of

the anode, resulting from higher current density.

ENDURANCE LIMIT

The maximum stress that a material can withstand for an infinitely large number of fatigue cycles.

ENVIRONMENT

The surroundings or conditions (physical, chemical, mechanical) in which a material exists.

ENVIRONMENTAL CRACKING

Brittle fracture of a normally ductile material in which the corrosive effect of the environment is a causative factor.

Environmental cracking is a general term that includes all of the terms listed below. The definitions of these terms are listed elsewhere in the *Glossary*:

- Corrosion Fatigue
- Hydrogen Embrittlement
- Hydrogen-Induced Cracking — (Stepwise Cracking)
- Hydrogen Stress Cracking
- Liquid Metal Cracking
- Stress Corrosion Cracking
- Sulfide Stress Cracking

The following terms have been used in the past in connection with environmental cracking but are now obsolete and should not be used:

- Caustic Embrittlement
- Delayed Cracking
- Liquid Metal Embrittlement
- Season Cracking
- Static Fatigue
- Sulfide Corrosion Cracking
- Sulfide Stress Corrosion Cracking

NACE GLOSSARY OF CORROSION-RELATED TERMS

EPOXY

Type of resin formed by the reaction of aliphatic or aromatic polyols (like bisphenol) with epichlorohydrin and characterized by the presence of reactive oxirane end groups.

EQUILIBRIUM POTENTIAL

The potential of an electrode in an electrolyte at which the forward rate of a given reaction is exactly equal to the reverse rate; the electrode potential with reference to a standard equilibrium, as defined by the Nernst equation.

EROSION

The progressive loss of material from a solid surface due to mechanical interaction between that surface and a fluid, a multicomponent fluid, or solid particles carried with the fluid.

EROSION-CORROSION

A conjoint action involving corrosion and erosion in the presence of a moving corrosive fluid or a material moving through the fluid, leading to accelerated loss of material.

EXCHANGE CURRENT

The rate at which either positive or negative charges are entering or leaving the surface when an electrode reaches dynamic equilibrium in an electrolyte.

EXFOLIATION CORROSION

Localized subsurface corrosion in zones parallel to the surface that result in thin layers of uncorroded metal resembling the pages of a book.

EXTERNAL CIRCUIT

The wires, connectors, measuring devices, current sources, etc., that are used to bring about or measure the desired electrical conditions within an electrochemical cell. It is this portion of the cell through which electrons travel.



FATIGUE

The phenomenon leading to fracture of a material under repeated or fluctuating stresses having a maximum value less than the tensile strength of the material.

FATIGUE STRENGTH

The maximum stress that can be sustained for a specified number of cycles without failure.

FAULT CURRENT

A current that flows from one conductor to ground or to another conductor due to an abnormal connection (including an arc) between the two. A fault current flowing to ground may be called a ground fault current.

FERRITE

The body-centered cubic crystalline phase of iron-based alloys.

FERRITIC STEEL

A steel whose microstructure at room temperature consists predominantly of ferrite.

FILIFORM CORROSION

Corrosion that occurs under a coating in the form of randomly distributed thread-like filaments.

FILM

A thin, not necessarily visible layer of material.

FINISH COAT

[See *Topcoat*.]

FORCED DRAINAGE

Drainage applied to underground or submerged metallic structures by means of an applied electromotive force or sacrificial anode.

FOREIGN STRUCTURE

Any metallic structure that is not intended as a part of a system under cathodic protection.

FOULING

An accumulation of deposits. This includes accumulation and growth of marine organisms on a submerged metal surface and the accumulation of deposits (usually inorganic) on heat exchanger tubing.

FRACTOGRAPHY

Descriptive treatment of fracture, especially in metals, with specific reference to photographs of the fracture surface.

FRACTURE MECHANICS

A quantitative analysis for evaluating structural reliability in terms of applied stress, crack length, and specimen geometry.

FREE MACHINING

The machining characteristics of an alloy to which an ingredient has been introduced to give small broken chips, lower power consumption, better surface finish, and longer tool life.

FRETTING CORROSION

Deterioration at the interface of

NACE GLOSSARY OF CORROSION-RELATED TERMS

two contacting surfaces under load which is accelerated by their relative motion.

FURAN

Type of resin formed by the polymerization or polycondensation of furfuryl, furfuryl alcohol, or other compounds containing a furan ring.



GALVANIC ANODE

A metal that provides sacrificial protection to another metal that is more noble when electrically coupled in an electrolyte. This type of anode is the electron source in one type of cathodic protection.

GALVANIC CORROSION

Accelerated corrosion of a metal because of an electrical contact with a more noble metal or nonmetallic conductor in a corrosive electrolyte.

GALVANIC COUPLE

A pair of dissimilar conductors, commonly metals, in electrical contact in an electrolyte.

GALVANIC CURRENT

The electric current between metals or conductive nonmetals in a galvanic couple.

GALVANIC SERIES

A list of metals and alloys arranged according to their corrosion potentials in a given environment.

GALVANOSTATIC

Refers to an experimental

technique whereby an electrode is maintained at a constant current in an electrolyte.

GENERAL CORROSION

Corrosion that is distributed more or less uniformly over the surface of a material.

GRAPHITIC CORROSION

Deterioration of gray cast iron in which the metallic constituents are selectively leached or converted to corrosion products, leaving the graphite intact.

GRAPHITIZATION

The formation of graphite in iron or steel, usually from decomposition of iron carbide at elevated temperatures. [Should not be used as a term to describe graphitic corrosion.]

GRIT

Small particles of hard material (e.g., iron, steel, or mineral) with irregular shapes that are commonly used as an abrasive in abrasive blast cleaning.

GRIT BLASTING

Abrasive blast cleaning using grit as the abrasive.

GROUND BED

One or more anodes installed below the earth's surface for the purpose of supplying cathodic protection.



HALF-CELL

A pure metal in contact with a solution of known concentration of its own ion, at a specific temperature, develops a potential

that is characteristic and reproducible; when coupled with another half-cell, an overall potential that is the sum of both half-cells develops.

HALF-CELL POTENTIAL

The potential in a given electrolyte of one electrode of a pair relative to a standard state or a reference state. Potentials can only be measured and expressed as the difference between the half-cell potentials of a pair of electrodes.

HAND TOOL CLEANING

Removal of loose rust, loose mill scale, and loose paint to degree specified, by hand chipping, scraping, sanding, and wire brushing. [See SSPC-SP 2.]

HARDENER

[See *Curing Agent*.]

HEAT-AFFECTED ZONE

That portion of the base metal that is not melted during brazing, cutting, or welding, but whose microstructure and properties are altered by the heat of these processes.

HEAT TREATMENT

Heating and cooling a solid metal or alloy in such a way as to obtain desired properties. Heating for the sole purpose of hot working is not considered heat treatment.

HIGH-PRESSURE WATER CLEANING

Water cleaning performed at pressures from 34 to 70 MPa (5,000 to 10,000 psig).

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HIGH-PRESSURE WATER JETTING

Water jetting performed at pressures from 70 to 170 MPa (10,000 to 25,000 psig).

HIGH-TEMPERATURE HYDROGEN ATTACK

A loss of strength and ductility of steel by high-temperature reaction of absorbed hydrogen with carbides in the steel, resulting in decarburization and internal fissuring.

HOLIDAY

A discontinuity in a protective coating that exposes unprotected surface to the environment.

HYDROGEN BLISTERING

The formation of subsurface planar cavities, called hydrogen blisters, in a metal resulting from excessive internal hydrogen pressure. Growth of near-surface blisters in low-strength metals usually results in surface bulges.

HYDROGEN EMBRITTLEMENT

A loss of ductility of a metal resulting from absorption of hydrogen.

HYDROGEN-INDUCED CRACKING

Stepwise internal cracks that connect adjacent hydrogen blisters on different planes in the metal, or to the metal surface (also known as *stepwise cracking*).

HYDROGEN OVERVOLTAGE

Overvoltage associated with the liberation of hydrogen gas.

HYDROGEN STRESS CRACKING

Cracking that results from the presence of hydrogen in a metal in combination with tensile stress. It occurs most frequently with high-strength alloys.



IMPINGEMENT CORROSION

A form of erosion-corrosion generally associated with the local impingement of a high-velocity, flowing fluid against a solid surface.

IMPRESSED CURRENT

An electric current supplied by a device employing a power source that is external to the electrode system. (An example is direct current for cathodic protection.)

IMPRESSED CURRENT ANODE

An electrode, suitable for use as an anode when connected to a source of impressed current, which is generally composed of a substantially inert material that conducts by oxidation of the electrolyte and, for this reason, is not corroded appreciably.

IMPULSE DIELECTRIC TEST

A method of applying voltage to an insulated wire through the use of electric pulses (usually 170 to 250 pulses per second) to determine the integrity of the wire's insulation.

INCLUSION

A nonmetallic phase such as an

oxide, sulfide, or silicate particle in a metal.

INORGANIC ZINC-RICH COATING

Coating containing a metallic zinc pigment (typically 75 wt% zinc or more in the dry film) in an inorganic vehicle.

INSTANT-OFF POTENTIAL

The polarized half-cell potential of an electrode taken immediately after the cathodic protection current is stopped, which closely approximates the potential without IR drop (i.e., the polarized potential) when the current was on.

INTERCRYSTALLINE CORROSION

[See *Intergranular Corrosion*.]

INTERDENDRITIC CORROSION

Corrosive attack of cast metals that progresses preferentially along paths between dendrites.

INTERFERENCE BOND

An intentional metallic connection, between metallic systems in contact with a common electrolyte, designed to control electrical current interchange between the systems.

INTERFERENCE CURRENT

[See *Stray Current*.]

INTERGRANULAR CORROSION

Preferential corrosion at or along the grain boundaries of a metal (also known as *intercrystalline*

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corrosion).

INTERGRANULAR STRESS CORROSION CRACKING

Stress corrosion cracking in which the cracking occurs along grain boundaries.

INTERNAL OXIDATION

The formation of isolated particles of oxidation products beneath the metal surface.

INTUMESCENCE

The swelling or bubbling of a coating usually caused by heating. [The term is commonly used in aerospace and fire-protection applications.]

ION

An electrically charged atom or group of atoms.

IR DROP

The voltage across a resistance in accordance with Ohm's Law.

IRON ROT

Deterioration of wood in contact with iron-based alloys.



KNIFE-LINE ATTACK

Intergranular corrosion of an alloy along a line adjoining or in contact with a weld after heating into the sensitization temperature range.



LAMELLAR CORROSION

[See *Exfoliation Corrosion*.]

LANGELIER INDEX

A calculated saturation index for calcium carbonate that is useful in predicting scaling behavior of natural water.

LINE CURRENT

The direct current flowing on a pipeline.

LINING

A coating or layer of sheet material adhered to or in intimate contact with the interior surface of a container used to protect the container against corrosion by its contents and/or to protect the contents of the container from contamination by the container material.

LIQUID METAL CRACKING

Cracking of a metal caused by contact with a liquid metal.

LONG-LINE CURRENT

Current through the earth between an anodic and a cathodic area that returns along an underground metallic structure.

LOW-CARBON STEEL

Steel having less than 0.30% carbon and no intentional alloying additions.

LOW-PRESSURE WATER CLEANING

Water cleaning performed at pressures less than 34 MPa (5,000 psig).

LUGGIN PROBE

A small tube or capillary filled with electrolyte, terminating close to the metal surface of an electrode under study, which is used to provide an ion-conducting path without diffusion between the electrode under study and a reference electrode.



MARTENSITE

A hard supersaturated solid solution of carbon in iron characterized by an acicular (needle-like) microstructure.

METAL DUSTING

The catastrophic deterioration of a metal exposed to a carbonaceous gas at elevated temperature.

METALLIZING

The coating of a surface with a thin metal layer by spraying, hot dipping, or vacuum deposition.

MILL SCALE

The oxide layer formed during hot fabrication or heat treatment of metals.

MIXED POTENTIAL

A potential resulting from two or more electrochemical reactions occurring simultaneously on one metal surface.

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MODULUS OF ELASTICITY

A measure of the stiffness or rigidity of a material. It is actually the ratio of stress to strain in the elastic region of a material. If determined by a tension or compression test, it is also called Young's Modulus or the coefficient of elasticity.



NATURAL DRAINAGE

Drainage from an underground or submerged metallic structure to a more negative (more anodic) structure, such as the negative bus of a trolley substation.

NEAR-WHITE BLAST CLEANED SURFACE

A near-white blast cleaned surface, when viewed without magnification, shall be free of all visible oil, grease, dust, dirt, mill scale, rust, coating, oxides, corrosion products, and other foreign matter. Random staining shall be limited to not more than 5% of each unit area of surface (approximately 58 cm² [9.0 in.²]), and may consist of light shadows, slight streaks, or minor discolorations caused by stains of rust, stains of mill scale, or stains of previously applied coating. [See NACE No. 2/SSPC-SP 10.]

NEGATIVE RETURN

A point of connection between the cathodic protection negative cable and the protected structure.

NERNST EQUATION

An equation that expresses the

exact electromotive force of an electrochemical cell in terms of the activities of products and reactants of the cell.

NERNST LAYER

The diffusion layer at the surface of an electrode in which the concentration of a chemical species is assumed to vary linearly from the value in the bulk solution to the value at the electrode surface.

NOBLE

The positive direction of electrode potential, thus resembling noble metals such as gold and platinum.

NOBLE METAL

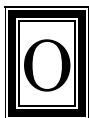
(1) A metal that occurs commonly in nature in the free state. (2) A metal or alloy whose corrosion products are formed with a small negative or a positive free-energy change.

NOBLE POTENTIAL

A potential more cathodic (positive) than the standard hydrogen potential.

NORMALIZING

Heating a ferrous alloy to a suitable temperature above the transformation range (austenitizing), holding at temperature for a suitable time, and then cooling in still air to a temperature substantially below the transformation range.



OPEN-CIRCUIT POTENTIAL

The potential of an electrode

measured with respect to a reference electrode or another electrode in the absence of current.

ORGANIC ZINC-RICH COATING

Coating containing a metallic zinc pigment (typically 75 wt% zinc or more in the dry film) in an organic resin.

OVERVOLTAGE

The change in potential of an electrode from its equilibrium or steady-state value when current is applied.

OXIDATION

(1) Loss of electrons by a constituent of a chemical reaction. (2) Corrosion of a metal that is exposed to an oxidizing gas at elevated temperatures.

OXIDATION-REDUCTION POTENTIAL

The potential of a reversible oxidation-reduction electrode measured with respect to a reference electrode, corrected to the hydrogen electrode, in a given electrolyte.

OXYGEN CONCENTRATION CELL

[See *Differential Aeration Cell*.]



PAINT

A pigmented liquid or resin applied to a substrate as a thin layer that is converted to an opaque solid film after application. It is commonly used

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as a decorative or protective coating.

PAINT SYSTEM

[See *Coating System*.]

PARTING

[See *Dealloying*.]

PASSIVATION

A reduction of the anodic reaction rate of an electrode involved in corrosion.

PASSIVATION POTENTIAL

[See *Primary Passive Potential*.]

PASSIVE

(1) The positive direction of electrode potential. (2) A state of a metal in which a surface reaction product causes a marked decrease in the corrosion rate relative to that in the absence of the product.

PASSIVE-ACTIVE CELL

An electrochemical cell, the electromotive force of which is caused by the potential difference between a metal in an active state and the same metal in a passive state.

PASSIVITY

The state of being passive.

PATINA

A thin layer of corrosion product, usually green, that forms on the surface of metals such as copper and copper-based alloys exposed to the atmosphere.

pH

The negative logarithm of the hydrogen ion activity written as:

$$\text{pH} = -\log_{10} (a_{\text{H}^+})$$

where a_{H^+} = hydrogen ion activity = the molar concentration of hydrogen ions multiplied by the mean ion-activity coefficient.

PICKLING

(1) Treating a metal in a chemical bath to remove scale and oxides (e.g., rust) from the surface. (2) Complete removal of rust and mill scale by acid pickling, duplex pickling, or electrolytic pickling. [See SSPC-SP 8.]

PICKLING SOLUTION

A chemical bath, usually an acid solution, used for pickling.

PIGMENT

A solid substance, generally in fine powder form, that is insoluble in the vehicle of a formulated coating material. It is used to impart color or other specific physical or chemical properties to the coating.

PIPE-TO-ELECTROLYTE POTENTIAL

[See *Structure-to-Electrolyte Potential*.]

PIPE-TO-SOIL POTENTIAL

[See *Structure-to-Electrolyte Potential*.]

PITTING

Localized corrosion of a metal surface that is confined to a small area and takes the form of cavities called pits.

PITTING FACTOR

The ratio of the depth of the deepest pit resulting from corrosion divided by the average penetration as calculated from mass loss.

PLASTIC DEFORMATION

Permanent deformation caused by stressing beyond the elastic limit.

PLASTICITY

The ability of a material to deform permanently (nonelastically) without fracturing.

POLARIZATION

The change from the open-circuit potential as a result of current across the electrode/electrolyte interface.

POLARIZATION ADMITTANCE

The reciprocal of polarization resistance.

POLARIZATION CELL

A DC decoupling device consisting of two or more pairs of inert metallic plates immersed in an aqueous electrolyte. The electrical characteristics of the polarization cell are high resistance to DC potentials and low impedance of AC.

POLARIZATION CURVE

A plot of current density versus electrode potential for a specific electrode/electrolyte combination.

POLARIZATION DECAY

The decrease in electrode potential with time resulting from the interruption of applied current.

POLARIZATION RESISTANCE

The slope (dE/di) at the corrosion potential of a potential (E)-current density (i) curve. (The measured slope is usually in good agreement with the true value of

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the polarization resistance when the scan rate is low and any uncompensated resistance is small relative to the polarization resistance.)

POLARIZED POTENTIAL

The potential across the structure/electrolyte interface that is the sum of the corrosion potential and the cathodic polarization.

POLYESTER

Type of resin formed by the condensation of polybasic and monobasic acids with polyhydric alcohols.

POSTWELD HEAT TREATMENT

Heating and cooling a weldment in such a way as to obtain desired properties.

POTENTIAL-pH DIAGRAM

A graphical method of representing the regions of thermodynamic stability of species for metal/electrolyte systems (also known as *Pourbaix diagram*).

POTENTIODYNAMIC

Refers to a technique wherein the potential of an electrode with respect to a reference electrode is varied at a selected rate by application of a current through the electrolyte.

POTENTIOKINETIC

[See *Potentiodynamic*.]

POTENTIOSTAT

An instrument for automatically maintaining a constant electrode potential.

POTENTIOSTATIC

Refers to a technique for maintaining a constant electrode potential.

POT LIFE

The elapsed time within which a coating can be effectively applied after all components of the coating have been thoroughly mixed.

POULTICE CORROSION

[See *Deposit Attack*.]

POURBAIX DIAGRAM

[See *Potential-pH Diagram*.]

POWER TOOL CLEANING

Removal of loose rust, loose mill scale, and loose paint to degree specified by power tool chipping, descaling, sanding, wire brushing, and grinding. [See SSPC-SP 3.]

PRECIPITATION HARDENING

Hardening caused by the precipitation of a constituent from a supersaturated solid solution.

PRIMARY PASSIVE POTENTIAL

The potential corresponding to the maximum active current density (critical anodic current density) of an electrode that exhibits active-passive corrosion behavior.

PRIME COAT

[See *Primer*.]

PRIMER

A coating material intended to be applied as the first coat on an uncoated surface. The coating is specifically formulated to adhere to and protect the surface as well as to produce a suitable surface

for subsequent coats. [Also referred to as *Prime Coat*.]

PROFILE

Anchor pattern on a surface produced by abrasive blasting or acid treatment.

PROTECTIVE COATING

A coating applied to a surface to protect the substrate from corrosion.



REDUCTION

Gain of electrons by a constituent of a chemical reaction.

REFERENCE ELECTRODE

An electrode whose open-circuit potential is constant under similar conditions of measurement, which is used for measuring the relative potentials of other electrodes.

REFERENCE HALF-CELL

[See *Reference Electrode*.]

RELATIVE HUMIDITY

The ratio, expressed as a percentage, of the amount of water vapor present in a given volume of air at a given temperature to the amount required to saturate the air at that temperature.

REMOTE EARTH

A location on the earth far enough from the affected structure that the soil potential gradients associated with currents entering the earth from the affected structure are

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insignificant.

RESISTIVITY

(1) The resistance per unit length of a substance with uniform cross section. (2) A measure of the ability of an electrolyte (e.g., soil) to resist the flow of electric charge (e.g., cathodic protection current). Resistivity data are used to design a groundbed for a cathodic protection system.

REST POTENTIAL

[See *Corrosion Potential*.]

REVERSIBLE POTENTIAL

[See *Equilibrium Potential*.]

RIMMED STEEL

An incompletely deoxidized steel. [Also called *Rimming Steel*.]

RISER

(1) That section of pipeline extending from the ocean floor up to an offshore platform. (2) The vertical tube in a steam generator convection bank that circulates water and steam upward.

RUST

Corrosion product consisting of various iron oxides and hydrated iron oxides. (This term properly applies only to iron and ferrous alloys.)

RUST BLOOM

Discoloration indicating the beginning of rusting.



SACKING

Scrubbing a mixture of a cement mortar over the concrete surface

using a cement sack, gunny sack, or sponge rubber float.

SACRIFICIAL ANODE

[See *Galvanic Anode*.]

SACRIFICIAL PROTECTION

Reduction of corrosion of a metal in an electrolyte by galvanically coupling it to a more anodic metal (a form of cathodic protection).

SCALING

(1) The formation at high temperatures of thick corrosion-product layers on a metal surface. (2) The deposition of water-insoluble constituents on a metal surface.

SCANNING ELECTRON MICROSCOPE

An electron optical device that images topographical details with maximum contrast and depth of field by the detection, amplification, and display of secondary electrons.

SENSITIZING HEAT TREATMENT

A heat treatment, whether accidental, intentional, or incidental (as during welding), that causes precipitation of constituents (usually carbides) at grain boundaries, often causing the alloy to become susceptible to intergranular corrosion or intergranular stress corrosion cracking.

SHALLOW GROUND BED

One or more anodes installed either vertically or horizontally at a nominal depth of less than 15 m (50 ft) for the purpose of supplying cathodic protection.

SHIELDING

(1) Protecting; protective cover against mechanical damage. (2) Preventing or diverting cathodic protection current from its natural path.

SHOP COAT

One or more coats applied in a shop or plant prior to shipment to the site of erection or fabrication.

SHOT BLASTING

Abrasive blast cleaning using metallic (usually steel) shot as the abrasive.

SHOT PEENING

Inducing compressive stresses in the surface layer of a material by bombarding it with a selected medium (usually steel shot) under controlled conditions.

SIGMA PHASE

An extremely brittle Fe-Cr phase that can form at elevated temperatures in Fe-Cr-Ni and Ni-Cr-Fe alloys.

SLIP

A deformation process involving shear motion of a specific set of crystallographic planes.

SLOW STRAIN RATE TECHNIQUE

An experimental technique for evaluating susceptibility to environmental cracking. It involves pulling the specimen to failure in uniaxial tension at a controlled slow strain rate while the specimen is in the test environment and examining the specimen for evidence of environmental cracking.

SLUSHING COMPOUND

Oil or grease coatings used to

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provide temporary protection against atmospheric corrosion.

SOLUTION HEAT TREATMENT

Heating a metal to a suitable temperature and holding at that temperature long enough for one or more constituents to enter into solid solution, then cooling rapidly enough to retain the constituents in solution.

SOLVENT CLEANING

Removal of oil, grease, dirt, soil, salts, and contaminants by cleaning with solvent, vapor, alkali, emulsion, or steam. [See SSPC-SP 1.]

SPALLING

The spontaneous chipping, fragmentation, or separation of a surface or surface coating.

STANDARD ELECTRODE POTENTIAL

The reversible potential for an electrode process when all products and reactions are at unit activity on a scale in which the potential for the standard hydrogen reference electrode is zero.

STANDARD JETTING WATER

Water of sufficient purity and quality that it does not impose additional contaminants on the surface being cleaned and does not contain sediments or other impurities that are destructive to the proper functioning of water jetting equipment.

STEEL SHOT

Small particles of steel with spherical shape that are commonly used as an abrasive in

abrasive blast cleaning or as a selected medium for shot peening.

STEP POTENTIAL

The potential difference between two points on the earth's surface separated by a distance of one human step, which is defined as one meter, determined in the direction of maximum potential gradient.

STEPWISE CRACKING

[See *Hydrogen-Induced Cracking*.]

STRAY CURRENT

Current through paths other than the intended circuit.

STRAY-CURRENT CORROSION

Corrosion resulting from current through paths other than the intended circuit, e.g., by any extraneous current in the earth.

STRESS CORROSION CRACKING

Cracking of a material produced by the combined action of corrosion and tensile stress (residual or applied).

STRESS RELIEVING (THERMAL)

Heating a metal to a suitable temperature, holding at that temperature long enough to reduce residual stresses, and then cooling slowly enough to minimize the development of new residual stresses.

STRUCTURE-TO-ELECTROLYTE POTENTIAL

The potential difference between the surface of a buried or submerged metallic structure and the electrolyte that is measured with reference to an electrode in contact with the electrolyte.

STRUCTURE-TO-SOIL POTENTIAL

[See *Structure-to-Electrolyte Potential*.]

STRUCTURE-TO-STRUCTURE POTENTIAL

The potential difference between metallic structures, or sections of the same structure, in a common electrolyte.

SUBSURFACE CORROSION

[See *Internal Oxidation*.]

SULFIDATION

The reaction of a metal or alloy with a sulfur-containing species to produce a sulfur compound that forms on or beneath the surface of the metal or alloy.

SULFIDE STRESS CRACKING

Cracking of a metal under the combined action of tensile stress and corrosion in the presence of water and hydrogen sulfide (a form of hydrogen stress cracking).

SURFACE POTENTIAL GRADIENT

Change in the potential on the surface of the ground with respect to distance.

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TACK COAT

A thin wet coat applied to the surface that is allowed to dry just until it is tacky before application of a thicker wet coat. (Use of a tack coat allows application of thicker coats without sagging or runs.)

TAFEL PLOT

A plot of the relationship between the change in potential (E) and the logarithm of the current density ($\log i$) of an electrode when it is polarized in both the anodic and cathodic directions from its open-circuit potential.

TAFEL SLOPE

The slope of the straight-line portion of the $E \log i$ curve on a Tafel plot. (The straight-line portion usually occurs at more than 50 mV from the open-circuit potential.)

TARNISH

Surface discoloration of a metal resulting from formation of a film of corrosion product.

THERMAL SPRAYING

A group of processes by which finely divided metallic or nonmetallic materials are deposited in a molten or semimolten condition to form a coating.

THERMOGALVANIC CORROSION

Corrosion resulting from an electrochemical cell caused by a thermal gradient.

THROWING POWER

The relationship between the current density at a point on a surface and its distance from the counterelectrode. The greater the ratio of the surface resistivity shown by the electrode reaction to the volume resistivity of the electrolyte, the better is the throwing power of the process.

TOPCOAT

The final coat of a coating system. [Also referred to as *Finish Coat*.]

TOUCH POTENTIAL

The potential difference between a metallic structure and a point on the earth's surface separated by a distance equal to the normal maximum horizontal reach of a human (approximately 1.0 m [3.3 ft]).

TRANSPASSIVE

The noble region of potential where an electrode exhibits a higher-than-passive current density.

TUBERCULATION

The formation of localized corrosion products scattered over the surface in the form of knob-like mounds called tubercles.



ULTIMATE STRENGTH

The maximum stress that a material can sustain.

ULTRAHIGH-PRESSURE WATER JETTING

Water jetting performed at pressures above 170 MPa (25,000 psig.)

UNDERFILM CORROSION

[See *Filiform Corrosion*.]

VEHICLE

The liquid portion of a formulated coating material.

VOID

(1) A holiday, hole, or skip in a coating. (2) A hole in a casting or weld deposit usually resulting from shrinkage during cooling.

WASH PRIMER

A thin, inhibiting primer, usually chromate pigmented, with a polyvinyl butyral binder.

WATER CLEANING

Use of pressurized water discharged from a nozzle to remove unwanted matter (e.g., dirt, scale, rust, coatings) from a surface.

WATER JETTING

Use of standard jetting water discharged from a nozzle at pressures of 70 MPa (10,000 psig) or greater to prepare a surface for coating or inspection.

WEIGHT COATING

An external coating applied to a pipeline to counteract buoyancy.

WHITE METAL BLAST CLEANED SURFACE

A white metal blast cleaned surface, when viewed without magnification, shall be free of all visible oil, grease, dust, dirt, mill scale, rust, coating, oxides, corrosion products, and other foreign matter. [See NACE No. 1/SSPC-SP 5.]

WELD DECAY

Intergranular corrosion, usually of

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stainless steel or certain nickel-base alloys, that occurs as the result of sensitization in the heat-affected zone during the welding operation. [This is not a preferred term.]

WET FILM GAUGE

Device for measuring wet film thickness of a coating.

WORKING ELECTRODE

The test or specimen electrode in an electrochemical cell.

WROUGHT

Metal in the solid condition that is formed to a desired shape by working (rolling, extruding, forging, etc.), usually at an elevated temperature.



YIELD POINT

The stress on a material at which the first significant permanent or plastic deformation occurs without an increase in stress. In some materials, particularly annealed low-carbon steels, there is a well-defined yield point from the straight line defining the modulus of elasticity.

YIELD STRENGTH

The stress at which a material exhibits a specified deviation from the proportionality of stress to strain. The deviation is expressed in terms of strain by either the offset method (usually at a strain of 0.2%) or the total-extension-under-load method (usually at a strain of 0.5%).

Factors Affecting the Accuracy of Reference Electrodes

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This article discusses several factors that affect the reference potential established by silver/silver chloride and copper/copper sulfate reference electrodes. Data is presented on the effects of temperature, light, contaminants, and solute concentration.

When measuring corrosion potential, a voltmeter is used to measure the potential (voltage) between the structure and a reference electrode placed in the same electrolyte. The entire circuit, structure plus reference, can be thought of as a single cell. Because a reference electrode comprises one half of this cell, it is commonly referred to as a "half-cell." Measured potentials are actually the difference in potential between that of the reference and that of the structure. It is frequently assumed that the potential established by a reference electrode is absolutely invariant; therefore, any observed potential changes must be occurring on the structure. This is not always the case. The observed changes could also be caused by a change in the reference while the structure remains steady. To ensure accurate potential measurements, it is important to understand those factors that affect the potential of a reference electrode.

Reference Electrode Classifications Element Types

In its most basic form, a reference electrode is simply a piece of metal immersed in a solution of one of its salts.¹ In a thermodynamically stable reference, a known reversible chemical reaction occurs between the metal element and its environment. At equilibrium, the reaction rate in both directions is equal and the potential established follows the Nernst equation.² In theory, the only factors that affect the potential of a reference electrode are temperature, which has a linear effect, and solution concentration, which has a logarithmic effect.

There are two kinds of reference electrode elements in common use. The first is a metal in a solution containing dissolved ions of that metal. An example of this is the copper/copper sulfate (Cu/CuSO_4) electrode. The second is a metal coated with a

salt of that metal and immersed in a solution of that salt. Both silver/silver chloride (Ag/AgCl) and calomel (mercury/mercury chloride) are electrodes of the second kind; their reference potential is established by the chloride ion concentration.

Electrolyte Types

Reference electrodes can also be classified by the form of the surrounding electrolyte. In dry electrodes, the element is directly immersed in the same electrolyte as the structure. The element is dry until it is placed in service; hence, the name. The silver/silver chloride/seawater reference is a well-known dry reference.³ Dry electrodes tend to be quite rugged and inexpensive. A disadvantage is that the reference potential they establish can change if the chemistry of the electrolyte changes. Also, the element of a dry electrode will be ruined if the electrolyte or the surrounding atmosphere during storage contains a contaminant for that type of electrode.

The contamination problem is greatly minimized by using a wet electrode, in which the element is

immersed in an electrolyte with a known salt concentration. This electrolyte should be renewed periodically. In use, the electrolyte will slowly leak into the environment through a porous plug. If a reverse-flow condition occurs, the element may become contaminated. Commonly used wet references include silver/silver chloride and saturated calomel for laboratory use and portable copper/copper sulfate for field use.

Because wet electrodes require periodic electrolyte replenishment, they are not suitable for permanent installation. To overcome this limitation, references intended for permanent use have a gelling agent added to the electrolyte. Gelled references require no maintenance. However, they do have a fixed lifetime. Like wet electrodes, gelled electrodes are subject to dry-out and contamination if they are not properly installed.

Reference Potential

The potential of a reference electrode is determined by the element metal and the active species concentration in the electrolyte. The form of the electrolyte, wet or gelled, has no effect on the reference potential. Figure 1 shows the potentials of commonly used reference electrodes. The potentials are shown relative to the saturated hydrogen electrode (SHE), which has been defined as the zero point on the potential scale. Note that there are two positions for the Ag/AgCl electrode: 1) saturated, which refers to a saturated potassium chloride (KCl) electrolyte; and 2) seawater, which refers to a dry electrode immersed in seawater. The reference potentials of these two electrodes are about 40 mV apart. The laboratory Ag/AgCl electrode, not shown in Figure 1, uses a filling solution of 4 M KCl, which is just under saturation. Its reference potential is about 7 mV positive to the saturated electrode.

When reporting corrosion potentials, it is important to describe the type of reference electrode used to measure the potentials. While the potential of a structure may not change

(Figure 2), the number used to describe that potential will depend on the type of electrode used to measure it. The commonly used criterion of -0.85 V for cathodically protected steel only refers to measurements made with copper/copper sulfate electrodes.

External Influences

Temperature, light, electrolyte concentration, and contamination all affect the potential of a reference electrode. These effects are most likely to affect portable references, which can operate in a variety of environments. Permanent electrodes most often operate where there is no light and usually in a very narrow temperature range. If they have been properly designed and installed, permanent electrodes are less likely to be influenced by changes in electrolyte concentration or contaminants. These points should be considered when a portable reference is used to calibrate an installed permanent reference: The observed variations may be due to a shift in the potential of the portable reference.

Temperature Effects

Temperature has both direct and indirect effects on reference potential. The direct effect is a linear variation of the reference potential with temperature. The indirect effect is that as temperature increases, the quantity of salt that can be dissolved in a saturated solution will also increase. This increase in salt concentration will affect potential. Only the linear variation will be seen in a nonsaturated electrode such as a 4 M or seawater Ag/AgCl electrode. Figure 3 shows the effect of temperature on the potential of electrodes in a fully saturated solution. These data include both the direct and indirect effects. The temperature coefficient for a saturated Cu/CuSO₄ electrode is about $0.5 \text{ mV}/^\circ\text{F}$ ($0.9 \text{ mV}/^\circ\text{C}$). Saturated Ag/AgCl electrodes have a much lower temperature coefficient: $-0.07 \text{ mV}/^\circ\text{F}$ ($-0.13 \text{ mV}/^\circ\text{C}$).

These temperature coefficients are large enough to produce a significant error in potential measurements

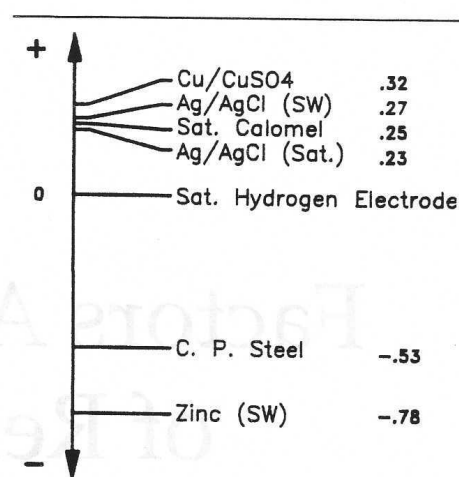


FIGURE 1
Relative potentials of common reference electrodes vs the saturated hydrogen electrode.

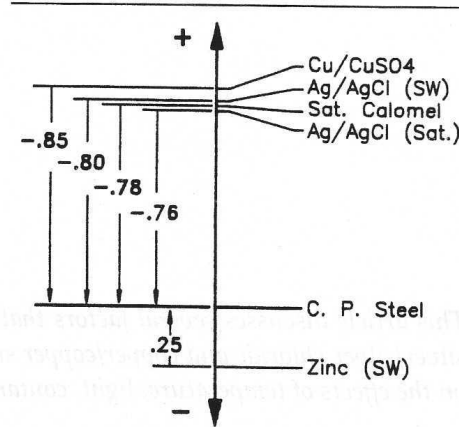


FIGURE 2
Potential of cathodically protected steel as measured by several common reference electrodes.

if they are left uncompensated. For example, the potential of a pipeline may be -865 mV when measured with a portable Cu/CuSO₄ electrode on a 90°F (26°C) day. If the same measurement were made on a 40°F (5°C) day, the temperature effect will cause a 25-mV shift in the reference potential so the pipeline would now measure -840 mV . The drift occasionally reported to occur on buried permanent electrodes is also likely due to temperature-caused drift of the portable electrode being used for calibration. When using a portable reference in the field, it is a good practice to record the ambient temperature and, if necessary, correct the readings.

Light Effects

Copper salts and silver salts are both photosensitive, so it should not be surprising that light has an effect

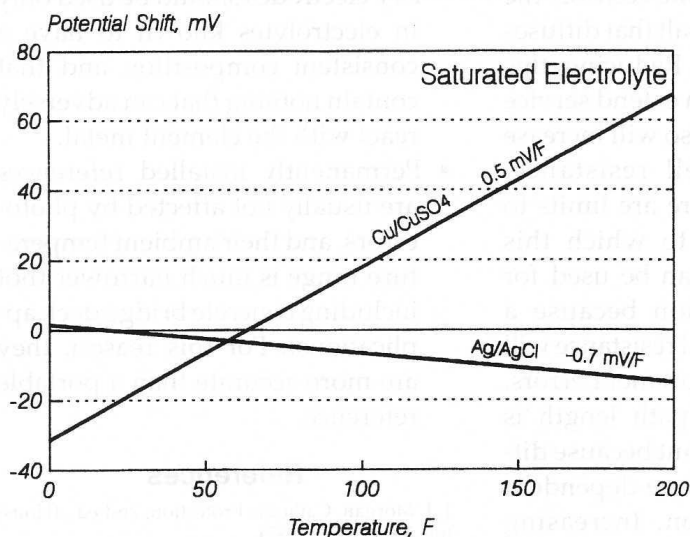


FIGURE 3

Effect of temperature on the reference potential of electrodes in a saturated electrolyte.

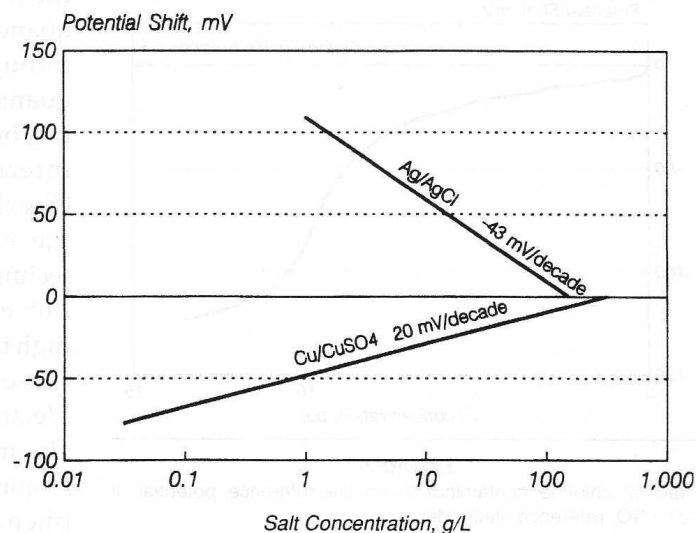


FIGURE 4

Effect of electrolyte concentration on the reference potential of Cu/CuSO_4 and Ag/AgCl reference electrodes.

on the reference potential. To measure this effect, special electrodes were made up in which two elements shared the same electrolyte. One element was kept permanently in the dark by a double baffle, while the other was exposed directly to ambient light. The magnitude of the light effect on Ag/AgCl electrodes was usually less than a millivolt, so it could be safely ignored. Cu/CuSO_4 electrodes, however, showed a high degree of light sensitivity. At high noon on the summer solstice, a copper element in direct sunlight measured -52 mV vs a second element kept in total darkness. In open shade, the value was closer to -10 mV, while interior fluorescent lights caused a -2 -mV shift. When the element was removed to a dark location and then re-exposed the following day, potential shifts of a similar magnitude were again observed. However, when the element was left in the sun for several hours, it apparently became desensitized, and subsequent photo-errors seldom exceeded -10 mV.

Housings of commercial portable electrodes are usually transparent red or yellow with a clear stripe to check the liquid level. When the direct illumination was through the red portion, no photo-error was observed, but if the illumination was through the clear stripe, then values similar to those above were measured. To get

consistent readings with a portable reference, the photo-error must be eliminated: The simplest way would be to place a strip of tape over the clear window. Permanent electrodes do not have this problem because they are usually installed in dark locations and have opaque housings.

Electrolyte Concentration Effects

The reference potential will vary with the logarithm of the concentration of active species in the cell electrolyte. This will cause variations in potential readings when using dry electrodes in an electrolyte in which the composition changes, such as Ag/AgCl /seawater references in a tidal estuary. The electrolyte of wet and gelled references has a constant composition that eliminates this source of uncertainty. The concentration coefficient for Cu/CuSO_4 electrodes is about 20 mV/decade in the negative direction (Figure 4). This means that for each order-of-magnitude drop in the concentration of CuSO_4 in the electrolyte, the reference potential will shift 20 mV in the negative direction. For Ag/AgCl references, the concentration coefficient is about 43 mV/decade in the positive direction.

Contamination Effects

Contamination of the electrolyte will alter the reference potential of an

electrode because competing chemical reactions, each with its own characteristic potential, are occurring simultaneously. The actual potential of the electrode then becomes a composite of all the potentials established by the individual reactions. Very often, the effect is permanent if the compound formed between the element metal and the contaminant is more stable than the compound formed as part of the reference electrode's intended reaction. Chlorides are the contaminant most likely to cause a problem with a Cu/CuSO_4 reference. The effect (Figure 5) is to shift the reference potential in the negative direction. Other halides (iodine, bromine) and sulfides will have a similarly deleterious effect on both Cu/CuSO_4 and Ag/AgCl electrodes. Sulfides in the atmosphere will even affect dry Ag/AgCl references in storage if proper precautions are not taken to protect them.

Design Life of Permanent (Gel) Cells

The useful life of a dry or wet reference electrode can be indefinite if it is properly maintained. A gel electrode, on the other hand, has a fixed life expectancy. In both wet and gel electrodes, a composition difference exists across the membrane separating the element's electrolyte from the environment. This difference acts

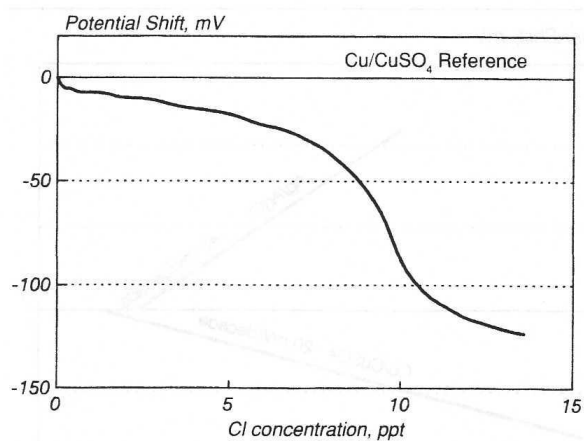


FIGURE 5

Effect of chloride contamination on the reference potential of Cu/CuSO₄ reference electrodes.

as a driving force for diffusion, which is outward for the active species and inward for contaminants. As diffusion changes the composition of the electrolyte, the reference potential changes. In a gel electrode, this change is permanent because the electrolyte cannot be renewed. Methods used to extend the life of a permanent reference electrode, therefore, must focus on extending the time before the effects of diffusion reach the element-electrolyte interface where the reference potential is established.

Three broad factors affect the service life of a permanent reference electrode: the environment in which it operates; the chemical make-up of the gel; and the physical design of the electrode itself. Environmental effects include both temperature and concentration difference across the membrane. Increasing either one will reduce service life by increasing diffusion rate. Permanent electrodes use a saturated salt solution as the basis for the electrolyte gel. The chemical make-up of the gel can be modified to provide a reserve of salt to make up for that which is lost by diffusion. Both the amount and distribution of this reserve affects electrode life. There are limits, however, to the amount of excess that can be added to the gel before its properties are affected.

Two design details of an electrode have a significant effect on service life: membrane type and electrolyte path length. The nature of

the membrane controls the quantity of salt that diffuses through it. Reducing this quantity can extend service life, but it also will increase internal cell resistance. Clearly, there are limits to the extent to which this technique can be used for life extension because a high internal resistance will cause measurement errors. Electrolyte path length is also important because diffusion is a time-dependent phenomenon. Increasing the internal electrolyte path length, that is, the distance from the element to the membrane, increases the time for the effects of diffusion to reach the element-gel interface where the reference potential is established. This factor is particularly significant when using gels with low ionic mobility. When the electrolyte next to the element becomes diluted, the reference potential will shift, ending the useful life of the electrode.

Another very important design criterion for a permanent reference electrode is that it be engineered specifically for its intended service. There are a wide variety of applications for permanent reference electrodes. For each application, it is necessary to consider such factors as size limitations, ambient temperature range, operating pressure, and installation procedures. If these requirements are ignored, service life will be drastically shortened.⁴

Conclusions

- Accurate readings with portable references require that the ambient temperature be recorded and a temperature correction be applied.
- Light striking the element of a portable Cu/CuSO₄ reference through the clear-view window can induce significant photo-errors. This window should be covered with dark tape.
- Portable references should be cleaned and the electrolyte replaced on a regular basis for them to maintain accuracy.

- Dry electrodes should be used only in electrolytes known to have a consistent composition and that contain nothing that can adversely react with the element metal.
- Permanently installed references are usually not affected by photo-errors, and their ambient temperature range is much narrower (not including concrete bridge deck applications). For this reason, they are more accurate than a portable reference.

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More information is available in CORROSION/94 paper no. 323, presented in Baltimore, Maryland.



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Standard Recommended Practice

Control of External Corrosion on Underground or Submerged Metallic Piping Systems

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Reaffirmed 2002-04-11
Revised 1972, 1976, 1983, 1992
Approved 1969
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ISBN 1-57590-035-1
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Foreword

This standard recommended practice presents procedures and practices for achieving effective control of external corrosion on buried or submerged metallic piping systems. These recommendations are also applicable to many other buried or submerged metallic structures. It is intended for use by corrosion control personnel concerned with the corrosion of buried or submerged piping systems, including oil, gas, water, and similar structures. This standard describes the use of electrically insulating coatings, electrical isolation, and cathodic protection as external corrosion control methods. It contains specific provisions for the application of cathodic protection to existing bare, existing coated, and new piping systems. Also included are procedures for control of interference currents on pipelines.

This standard should be used in conjunction with the practices described in the following NACE standards and publications when appropriate (use latest revisions):

RP0572¹

RP0177²

RP0285³

RP0186⁴

RP0286⁵

RP0387⁶

RP0188⁷

TPC 11⁸

TM0497⁹

For accurate and correct application of this standard, the standard must be used in its entirety. Using or citing only specific paragraphs or sections can lead to misinterpretation and misapplication of the recommendations and practices contained in this standard.

This standard does not designate practices for every specific situation because of the complexity of conditions to which buried or submerged piping systems are exposed.

This standard was originally published in 1969, and was revised by NACE Task Group T-10-1 in 1972, 1976, 1983, and 1992. It was reaffirmed in 1996 by NACE Unit Committee T-10A on Cathodic Protection, and in 2002 by Specific Technology Group (STG) 35 on Pipelines, Tanks, and Well Casings. This standard is issued by NACE International under the auspices of STG 35, which is composed of corrosion control personnel from oil and gas transmission companies, gas distribution companies, power companies, corrosion consultants, and others concerned with external corrosion control of buried or submerged metallic piping systems.

In NACE standards, the terms *shall*, *must*, *should*, and *may* are used in accordance with the definitions of these terms in the *NACE Publications Style Manual*, 4th ed., Paragraph 7.4.1.9. *Shall* and *must* are used to state mandatory requirements. The term *should* is used to state something considered good and is recommended but is not mandatory. The term *may* is used to state something considered optional.

**NACE International
Standard
Recommended Practice**

**Control of External Corrosion on Underground
or Submerged Metallic Piping Systems**

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Section 1: General

1.1 This standard presents acknowledged practices for the control of external corrosion on buried or submerged steel, cast iron, ductile iron, copper, and aluminum piping systems.

1.2 This standard is intended to serve as a guide for establishing minimum requirements for control of external corrosion on the following systems:

1.2.1 New piping systems: Corrosion control by a coating supplemented with cathodic protection, or by some other proven method, should be provided in the initial design and maintained during the service life of the piping system, unless investigations indicate that corrosion control is not required. Consideration should be given to the construction of pipelines in a manner that facilitates the use of in-line inspection tools.

1.2.2 Existing coated piping systems: Cathodic protection should be provided and maintained, unless investigations indicate that cathodic protection is not required.

1.2.3 Existing bare piping systems: Studies should be made to determine the extent and rate of corrosion on existing bare piping systems. When these studies indicate that corrosion will affect the safe or economic operation of the system, adequate corrosion control measures shall be taken.

1.3 The provisions of this standard should be applied under the direction of competent persons who, by reason of knowledge of the physical sciences and the principles of engineering and mathematics, acquired by education and related practical experience, are qualified to engage in the practice of corrosion control on buried or submerged metallic piping systems. Such persons may be registered professional engineers or persons recognized as corrosion specialists or cathodic protection specialists by NACE if their professional activities include suitable experience in external corrosion control of buried or submerged metallic piping systems.

1.4 Special conditions in which cathodic protection is ineffective or only partially effective sometimes exist. Such conditions may include elevated temperatures, disbonded coatings, thermal insulating coatings, shielding, bacterial attack, and unusual contaminants in the electrolyte. Deviation from this standard may be warranted in specific situations provided that corrosion control personnel in responsible charge are able to demonstrate that the objectives expressed in this standard have been achieved.

1.5 This standard does not include corrosion control methods based on chemical control of the environment, on the use of electrically conductive coatings, or on control of internal corrosion.

Section 2: Definitions⁽¹⁾

Amphoteric Metal: A metal that is susceptible to corrosion in both acid and alkaline environments.

Anode: The electrode of an electrochemical cell at which oxidation occurs. Electrons flow away from the anode in the external circuit. Corrosion usually occurs and metal ions enter solution at the anode.

Anodic Polarization: The change of the electrode potential in the noble (positive) direction caused by current across the electrode/electrolyte interface.

Beta Curve: A plot of dynamic (fluctuating) interference current or related proportional voltage (ordinate) versus values of corresponding structure-to-soil potentials at a selected location on the affected structure (abscissa) (see Appendix A).

Cable: One conductor or multiple conductors insulated from one another.

Cathode: The electrode of an electrochemical cell at which reduction is the principal reaction. Electrons flow toward the cathode in the external circuit.

Cathodic Disbondment: The destruction of adhesion between a coating and the coated surface caused by products of a cathodic reaction.

Cathodic Polarization: The change of electrode potential in the active (negative) direction caused by current across the electrode/electrolyte interface.

⁽¹⁾ Definitions in this section reflect common usage among practicing corrosion control personnel and apply specifically to how the terms are used in this standard. In many cases, in the interests of brevity and practical usefulness, the scientific definitions are abbreviated or paraphrased.

Cathodic Protection: A technique to reduce the corrosion of a metal surface by making that surface the cathode of an electrochemical cell.

Coating: A liquid, liquefiable, or mastic composition that, after application to a surface, is converted into a solid protective, decorative, or functional adherent film.

Coating Disbondment: The loss of adhesion between a coating and the pipe surface.

Conductor: A material suitable for carrying an electric current. It may be bare or insulated.

Continuity Bond: A connection, usually metallic, that provides electrical continuity between structures that can conduct electricity.

Corrosion: The deterioration of a material, usually a metal, that results from a reaction with its environment.

Corrosion Potential (E_{corr}): The potential of a corroding surface in an electrolyte relative to a reference electrode under open-circuit conditions (also known as *rest potential*, *open-circuit potential*, or *freely corroding potential*).

Corrosion Rate: The rate at which corrosion proceeds.

Criterion: Standard for assessment of the effectiveness of a cathodic protection system.

Current Density: The current to or from a unit area of an electrode surface.

Diode: A bipolar semiconducting device having a low resistance in one direction and a high resistance in the other.

Distributed-Anode Impressed Current System: An impressed current anode configuration in which the anodes are “distributed” along the structure at relatively close intervals such that the structure is within each anode’s voltage gradient. This anode configuration causes the electrolyte around the structure to become positive with respect to remote earth.

Electrical Isolation: The condition of being electrically separated from other metallic structures or the environment.

Electrical Survey: Any technique that involves coordinated electrical measurements taken to provide a basis for deduction concerning a particular electrochemical condition relating to corrosion or corrosion control.

Electrode: A conductor used to establish contact with an electrolyte and through which current is transferred to or from an electrolyte.

Electroosmotic Effect: Passage of a charged particle through a membrane under the influence of a voltage. Soil or coatings may act as the membrane.

Electrolyte: A chemical substance containing ions that migrate in an electric field. For the purpose of this standard, electrolyte refers to the soil or liquid adjacent to and in contact with a buried or submerged metallic piping system, including the moisture and other chemicals contained therein.

Foreign Structure: Any metallic structure that is not intended as a part of a system under cathodic protection.

Galvanic Anode: A metal that provides sacrificial protection to another metal that is more noble when electrically coupled in an electrolyte. This type of anode is the electron source in one type of cathodic protection.

Galvanic Series: A list of metals and alloys arranged according to their corrosion potentials in a given environment.

Holiday: A discontinuity in a protective coating that exposes unprotected surface to the environment.

Impressed Current: An electric current supplied by a device employing a power source that is external to the electrode system. (An example is direct current for cathodic protection.)

In-Line Inspection: The inspection of a steel pipeline using an electronic instrument or tool that travels along the interior of the pipeline.

Insulating Coating System: All components of the protective coating, the sum of which provides effective electrical isolation of the coated structure.

Interference: Any electrical disturbance on a metallic structure as a result of stray current.

Interference Bond: A metallic connection designed to control electrical current interchange between metallic systems.

IR Drop: The voltage across a resistance in accordance with Ohm’s Law.

Isolation: See *Electrical Isolation*.

Line Current: The direct current flowing on a pipeline.

Long-Line Corrosion Activity: Current through the earth between an anodic and a cathodic area that returns along an underground metallic structure.

Mixed Potential: A potential resulting from two or more electrochemical reactions occurring simultaneously on one metal surface.

Pipe-to-Electrolyte Potential: The potential difference between the pipe metallic surface and electrolyte that is measured with reference to an electrode in contact with the electrolyte.

Polarization: The change from the open-circuit potential as a result of current across the electrode/electrolyte interface.

Polarized Potential: The potential across the structure/electrolyte interface that is the sum of the corrosion potential and the cathodic polarization.

Reference Electrode: An electrode whose open-circuit potential is constant under similar conditions of measurement, which is used for measuring the relative potentials of other electrodes.

Reverse-Current Switch: A device that prevents the reversal of direct current through a metallic conductor.

Shielding: Preventing or diverting the cathodic protection current from its intended path.

Shorted Pipeline Casing: A casing that is in direct metallic contact with the carrier pipe.

Sound Engineering Practices: Reasoning exhibited or based on thorough knowledge and experience, logically valid and having technically correct premises that demonstrate good judgment or sense in the application of science.

Stray Current: Current through paths other than the intended circuit.

Stray-Current Corrosion: Corrosion resulting from current through paths other than the intended circuit, e.g., by any extraneous current in the earth.

Telluric Current: Current in the earth as a result of geomagnetic fluctuations.

Voltage: An electromotive force or a difference in electrode potentials expressed in volts.

Wire: A slender rod or filament of drawn metal. In practice, the term is also used for smaller-gauge conductors (6 mm² [No. 10 AWG⁽²⁾] or smaller).

Section 3: Determination of Need for External Corrosion Control

3.1 Introduction

3.1.1 This section recommends practices for determining when an underground or submerged metallic piping system requires external corrosion control.

3.1.2 Metallic structures, buried or submerged, are subject to corrosion. Adequate corrosion control procedures should be adopted to ensure metal integrity for safe and economical operation.

3.2 The need for external corrosion control should be based on data obtained from one or more of the following: corrosion surveys, operating records, visual observations, test results from similar systems in similar environments, in-line inspections, engineering and design specifications, and operating, safety, and economic requirements. The absence of leaks alone is insufficient evidence that corrosion control is not required.

3.2.1 Environmental and physical factors include the following:

3.2.1.1 Corrosion rate of the particular metallic piping system in a specific environment (see Appendix B);

3.2.1.2 Nature of the product being transported, the working temperature, temperature differentials within the pipeline causing thermal expansion and contraction, tendency of backfill to produce soil stress, and working pressure of the piping system as related to design specification;

3.2.1.3 Location of the piping system as related to population density and frequency of visits by personnel;

3.2.1.4 Location of the piping system as related to other facilities; and

3.2.1.5 Stray current sources foreign to the system.

3.2.2 Economic factors include the following:

3.2.2.1 Costs of maintaining the piping system in service for its expected life (see Appendix B);

3.2.2.2 Contingent costs of corrosion (see Appendix C); and

3.2.2.3 Costs of corrosion control (see Appendix D).

⁽²⁾ American Wire Gauge.

Section 4: Piping System Design

4.1 Introduction

4.1.1 This section provides accepted corrosion control practices in the design of an underground or submerged piping system. A person qualified to engage in the practice of corrosion control should be consulted during all phases of pipeline design and construction (see Paragraph 1.3). These recommendations should not be construed as taking precedence over recognized electrical safety practices.

4.2 External Corrosion Control

4.2.1 External corrosion control must be a primary consideration during the design of a piping system. Materials selection and coatings are the first line of defense against external corrosion. Because perfect coatings are not feasible, cathodic protection must be used in conjunction with coatings. For additional information, see Sections 5 and 6.

4.2.2 New piping systems should be externally coated unless thorough investigation indicates that coatings are not required (see Section 5).

4.2.3 Materials and construction practices that create electrical shielding should not be used on the pipeline. Pipelines should be installed at locations where proximity to other structures and subsurface formations do not cause shielding.

4.3 Electrical Isolation

4.3.1 Isolation devices such as flange assemblies, prefabricated joint unions, or couplings should be installed within piping systems where electrical isolation of portions of the system is required to facilitate the application of external corrosion control. These devices should be properly selected for temperature, pressure, chemical resistance, dielectric resistance, and mechanical strength. Installation of isolation devices should be avoided or safeguarded in areas in which combustible atmospheres are likely to be present. Locations at which electrical isolating devices should be considered include, but are not limited to, the following:

4.3.1.1 Points at which facilities change ownership, such as meter stations and well heads;

4.3.1.2 Connections to main-line piping systems, such as gathering or distribution system laterals;

4.3.1.3 Inlet and outlet piping of in-line measuring and/or pressure-regulating stations;

4.3.1.4 Compressor or pumping stations, either in the suction and discharge piping or in the main line immediately upstream and downstream from the station;

4.3.1.5 Stray current areas;

4.3.1.6 The junction of dissimilar metals;

4.3.1.7 The termination of service line connections and entrance piping;

4.3.1.8 The junction of a coated pipe and a bare pipe; and

4.3.1.9 Locations at which electrical grounding is used, such as motorized valves and instrumentation.

4.3.2 The need for lightning and fault current protection at isolating devices should be considered. Cable connections from isolating devices to arresters should be short, direct, and of a size suitable for short-term high-current loading.

4.3.3 When metallic casings are required as part of the underground piping system, the pipeline should be electrically isolated from such casings. Casing insulators must be properly sized and spaced and be tightened securely on the pipeline to withstand insertion stresses without sliding on the pipe. Inspection should be made to verify that the leading insulator has remained in position. Concrete coatings on the carrier pipe could preclude the use of casing insulators. Consideration should be given to the use of support under the pipeline at each end of the casing to minimize settlement. The type of support selected should not cause damage to the pipe coating or act as a shield to cathodic protection current.

4.3.4 Casing seals should be installed to resist the entry of foreign matter into the casing.

4.3.5 When electrical contact would adversely affect cathodic protection, piping systems should be electrically isolated from supporting pipe stanchions, bridge structures, tunnel enclosures, pilings, offshore structures, or reinforcing steel in concrete. However, piping can be attached directly to a bridge without isolation if isolating devices are installed in the pipe system on each side of the bridge to electrically isolate the bridge piping from adjacent underground piping.

4.3.6 When an isolating joint is required, a device manufactured to perform this function should be used, or, if permissible, a section of nonconductive pipe, such as plastic pipe, may be installed. In either case, these

should be properly rated and installed in accordance with the manufacturer's instructions.

4.3.7 River weights, pipeline anchors, and metallic reinforcement in weight coatings should be electrically isolated from the carrier pipe and designed and installed so that coating damage does not occur and the carrier pipe is not electrically shielded.

4.3.8 Metallic curb boxes and valve enclosures should be designed, fabricated, and installed in such a manner that electrical isolation from the piping system is maintained.

4.3.9 Insulating spacing materials should be used when it is intended to maintain electrical isolation between a metallic wall sleeve and the pipe.

4.3.10 Underground piping systems should be installed so that they are physically separated from all foreign underground metallic structures at crossings and parallel installations and in such a way that electrical isolation could be maintained if desired.

4.3.11 Based on voltage rating of alternating current (AC) transmission lines, adequate separation should be maintained between pipelines and electric transmission tower footings, ground cables, and counterpoise. Regardless of separation, consideration should always be given to lightning and fault current protection of pipeline(s) and personnel safety (see NACE Standard RP0177²).

4.4 Electrical Continuity

4.4.1 Nonwelded pipe joints may not be electrically continuous. Electrical continuity can be ensured by the use of fittings manufactured for this purpose or by bonding across and to the mechanical joints in an effective manner.

4.5 Corrosion Control Test Stations

4.5.1 Test stations for potential, current, or resistance measurements should be provided at sufficient locations to facilitate cathodic protection testing. Such locations may include, but not be limited to, the following:

- 4.5.1.1 Pipe casing installations,
- 4.5.1.2 Metallic structure crossings,
- 4.5.1.3 Isolating joints,
- 4.5.1.4 Waterway crossings,
- 4.5.1.5 Bridge crossings,
- 4.5.1.6 Valve stations,
- 4.5.1.7 Galvanic anode installations,

4.5.1.8 Road crossings,

4.5.1.9 Stray-current areas, and

4.5.1.10 Rectifier installations.

4.5.2 The span of pipe used for line current test stations should exclude:

4.5.2.1 Foreign metallic structure crossings;

4.5.2.2 Lateral connections;

4.5.2.3 Mechanical couplings or connections such as screwed joints, transition pieces, valves, flanges, anode or rectifier attachments, or metallic bonds; and

4.5.2.4 Changes in pipe wall thickness and diameter.

4.5.3 Attachment of Copper Test Lead Wires to Steel and Other Ferrous Pipes

4.5.3.1 Test lead wires may be used both for periodic testing and for current-carrying purposes. As such, the wire/pipe attachment should be mechanically strong and electrically conductive.

4.5.3.2 Methods of attaching wires to the pipe include (a) thermit welding process, (b) soldering, and (c) mechanical means.

4.5.3.3 Particular attention must be given to the attachment method to avoid (a) damaging or penetrating the pipe, (b) sensitizing or altering of pipe properties, (c) weakening the test lead wire, (d) damaging internal or external pipe coatings, and (e) creating hazardous conditions in explosive environments.

4.5.3.4 Attachment by mechanical means is the least desirable method. Such a connection may loosen, become highly resistant, or lose electrical continuity.

4.5.3.5 The connection should be tested for mechanical strength and electrical continuity. All exposed portions of the connection should be thoroughly cleaned of all welding slag, dirt, oils, etc.; primed, if needed; and coated with materials compatible with the cable insulation, pipe coating, and environment.

4.5.4 Attachment of Aluminum Test Lead Wire to Aluminum Pipes

4.5.4.1 Aluminum test lead wire, or aluminum tabs attached to aluminum wire, may be welded to aluminum pipe using the tungsten inert-gas shielded arc (TIG) or metal inert-gas shielded arc (MIG) process. Welded attachments should be

made to flanges or at butt weld joints. Attachment at other sites may adversely affect the mechanical properties of the pipe because of the heat of welding.

4.5.4.2 Test lead wire may be attached to aluminum pipe by soldering. If low-melting-point soft solders are used, a flux is required. Flux residues may cause corrosion unless removed.

NOTE: The use of copper test lead wire may cause preferential galvanic attack on the aluminum pipe. When copper wire or flux is used, care must be taken to seal the attachment areas against moisture. In the presence of moisture, the connection may disbond and be damaged by corrosion.

4.5.4.3 Aluminum tabs to which test lead wires have been TIG welded can be attached by an explosive bonding technique called high-energy joining.

4.5.4.4 Mechanical connections that remain secure and electrically conductive may be used.

4.5.5 Attachment of Copper Test Lead Wire to Copper Pipe

4.5.5.1 Copper test lead wire, or copper tabs attached to copper wire, may be attached to copper pipe by one of the following methods. The relative thickness of the wire and the pipe wall dictates, in part, which of the methods can be used.

4.5.5.1.1 Arc welding (TIG, MIG, or shielded metal);

4.5.5.1.2 Electrical resistance (spot) welding;

4.5.5.1.3 Brazing;

4.5.5.1.4 Soldering; or

4.5.5.1.5 Mechanical connection.

4.5.5.2 Attention should be given to proper joining procedures to avoid possible embrittlement or loss of mechanical properties of the metals from the heat of welding or brazing.

4.5.5.3 A flux may be required, or self-produced, when brazing with some filler metals or soldering with some low-melting-point soft solders. Because flux residues may cause corrosion, they should be removed.

Section 5: External Coatings

5.1 Introduction

5.1.1 This section recommends practices for selecting, testing and evaluating, handling, storing, inspecting, and installing external coating systems for external corrosion control on piping systems.

The function of external coatings is to control corrosion by isolating the external surface of the underground or submerged piping from the environment, to reduce cathodic protection current requirements, and to improve current distribution.

5.1.3 External coatings must be properly selected and applied and the coated piping carefully handled and installed to fulfill these functions. Various types of external coatings can accomplish the desired functions.

5.1.2.1 Desirable characteristics of external coatings include the following:

5.1.2.1.1 Effective electrical insulator;

5.1.2.1.2 Effective moisture barrier;

5.1.2.1.3 Application to pipe by a method that does not adversely affect the properties of the pipe;

5.1.2.1.4 Application to pipe with a minimum of defects;

5.1.2.1.5 Good adhesion to pipe surface;

5.1.2.1.6 Ability to resist development of holidays with time;

5.1.2.1.7 Ability to resist damage during handling, storage, and installation;

5.1.2.1.8 Ability to maintain substantially constant electrical resistivity with time;

5.1.2.1.9 Resistance to disbonding;

5.1.2.1.10 Resistance to chemical degradation;

5.1.2.1.11 Ease of repair;

5.1.2.1.12 Retention of physical characteristics;

5.1.2.1.13 Nontoxic to the environment; and

5.1.2.1.14 Resistance to changes and deterioration during aboveground storage and long-distance transportation.

5.1.2.2 Typical factors to consider when selecting an external pipe coating include:

5.1.2.2.1 Type of environment;

5.1.2.2.2 Accessibility of piping system;

5.1.2.2.3 Operating temperature of piping system;

5.1.2.2.4 Ambient temperatures during application, shipping, storage, construction, installation, and pressure testing;

5.1.2.2.5 Geographical and physical location;

5.1.2.2.6 Type of external coating on existing pipe in the system;

5.1.2.2.7 Handling and storage;

5.1.2.2.8 Pipeline installation methods;

5.1.2.2.9 Costs; and

5.1.2.2.10 Pipe surface preparation requirements.

5.1.2.3 Pipeline external coating systems shall be properly selected and applied to ensure that adequate bonding is obtained. Unbonded coatings can create electrical shielding of the pipeline that could jeopardize the effectiveness of the cathodic protection system.

5.1.3 Information in this section is primarily by reference to other documents. It is important that the latest revision of the pertinent reference be used.

5.1.3.1 Table 1 is a listing of types of external coating systems, showing the appropriate references for material specifications and recommended practices for application.

5.1.3.2 Table 2 is a grouping of references for general use during installation and inspection, regardless of coating type.

5.1.3.3 Table 3 is a list of external coating system characteristics related to environmental conditions containing suggested laboratory test references for various properties.

5.1.3.4 Table 4 is a list of external coating system characteristics related to design and construction, with recommended laboratory tests for evaluating these properties.

5.1.3.5 Table 5 lists the references that are useful in field evaluation of external coating systems after the pipeline has been installed.

5.2 Storage, Handling, Inspection, and Installation

5.2.1 Storage and Handling

5.2.1.1 Coated pipe to be stored should be protected internally and externally from atmospheric corrosion and coating deterioration.

5.2.1.2 Damage to coating can be minimized by careful handling and by using proper pads and slings.

TABLE 1
Generic External Coating Systems with Material Requirements
and Recommended Practices for Application^(A)

Generic External Coating System	Reference
Coal Tar	ANSI ^(B) /AWWA ^(C) C 203 ¹⁰
Wax	NACE Standard RP0375 ¹¹
Prefabricated Films	NACE Standard MR0274 ¹² ANSI/AWWA C 214 ¹³ ANSI/AWWA C 209 ¹⁴
Fusion-Bonded Epoxy Coatings	<i>Peabody's Control of Pipeline Corrosion</i> ¹⁵ ANSI/AWWA C 213 ¹⁶ API ^(D) RP 5L7 ¹⁷ CSA ^(E) Z245.20M ¹⁸ NACE Standard RP0190 ¹⁹
Polyolefin Coatings	NACE Standard RP0185 ²⁰ DIN ^(F) 30 670 ²¹ ANSI/AWWA C215 ²²

^(A) NOTE: Many other references are available and this table is not comprehensive. Listing does not constitute endorsement of any external coating system in preference to another. Omission of a system may be due to unavailability of reference standards or lack of data.

^(B) American National Standards Institute (ANSI), 1819 L Street, NW, Washington, DC 20036.

^(C) American Water Works Association (AWWA), 6666 West Quincy Ave., Denver, CO 80235.

^(D) American Petroleum Institute (API), 1220 L St. NW, Washington, DC 20005.

^(E) CSA International, 178 Rexdale Blvd., Toronto, Ontario, Canada M9W 1R3.

^(F) Deutsches Institut für Normung (DIN), Burggrafenstrasse 6, D-10787 Berlin, Germany.

TABLE 2
References for General Use in the Installation and Inspection of External Coating Systems
for Underground Piping

Subject	Reference
Application of Organic Pipeline Coatings	ANSI/AWWA C 203 ¹⁰ NACE Standard RP0375 ¹¹ <i>Peabody's Control of Pipeline Corrosion</i> ¹⁵ ANSI/AWWA C 213 ¹⁶ API RP 5L7 ¹⁷ CSA Z245.20M ¹⁸ NACE Standard RP0190 ¹⁹
Film Thickness of Pipeline Coatings	ASTM ^(A) G 128 ²³
Inspection of Pipeline Coatings	NACE Standard RP0274 ²⁴

^(A) ASTM, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959.

TABLE 3
External Coating System Characteristics Relative to Environmental Conditions^(A)

Environmental Factor	Recommended Test Methods^(B)
General underground exposure with or without cathodic protection	<i>Peabody's Control of Pipeline Corrosion</i> ¹⁵ ANSI/AWWA C 213 ¹⁶ API RP 5L7 ¹⁷ CSA Z245.20M ¹⁸ NACE Standard RP0190 ¹⁹ ASTM G 8 ²⁵ ASTM G 19 ²⁶ ASTM G 42 ²⁷ ASTM G 95 ²⁸
Resistance to water penetration and its effect on choice of coating thickness	ASTM G 9 ²⁹
Resistance to penetration by stones in backfill	ASTM G 17 ³⁰ ASTM D 2240 ³¹ ASTM G 13 ³² ASTM G 14 ³³
Soil stress	<i>Underground Corrosion</i> ³⁴ ASTM D 427 ³⁵
Resistance to specific liquid not normally encountered in virgin soil	ASTM D 543 ³⁶ Federal Test Standard ^(C) No. 406A, Method 7011 ³⁷ ASTM G 20 ³⁸
Resistance to thermal effects	ASTM D 2304 ³⁹ ASTM D 2454 ⁴⁰ ASTM D 2485 ⁴¹
Suitability of supplementary materials for joint coating and field repairs	ASTM G 8 ²⁵ ASTM G 19 ²⁶ ASTM G 42 ²⁷ ASTM G 95 ²⁸ ASTM G 9 ²⁹ ASTM G 18 ⁴² ASTM G 55 ⁴³
Resistance to microorganisms	ASTM G 21 ⁴⁴ Federal Test Standard No. 406A, Method 6091 ⁴⁵

^(A) NOTE: Apply only those factors pertinent to the installation.

^(B) No specific criteria are available. Comparative tests are recommended for use and evaluation as supplementary information only.

^(C) Available from General Services Administration, Business Service Center, Washington, DC 20025.

TABLE 4
External Coating System Characteristics Related to Design and Construction

Design and Construction Factor	Recommended Test Methods^(A)
Yard Storage, Weathering	ASTM G 11 ⁴⁶
Yard Storage, Penetration Under Load	ASTM G 17 ³⁰ ASTM D 2240 ³¹
Handling Resistance, Abrasion	ASTM G 6 ⁴⁷
Handling Resistance, Impact	ASTM G 13 ³² ASTM G 14 ³³
Field Bending Ability	ASTM G 10 ⁴⁸
Driving Ability (Resistance to Sliding Abrasion)	ASTM G 6 ⁴⁷ ASTM D 2197 ⁴⁹
Special Requirements for Mill-Applied Coating	ANSI/AWWA C 20 ⁴⁰ NACE Standard RP0375 ¹¹ NACE Standard MR0274 ¹² ANSI/AWWA C 214 ¹³ ANSI/AWWA C 209 ¹⁴ <i>Peabody's Control of Pipeline Corrosion</i> ¹⁵ ANSI/AWWA C 213 ¹⁶ API RP 5L7 ¹⁷ CSA Z245.20M ¹⁸ NACE Standard RP0190 ¹⁹ NACE Standard RP0185 ²⁰ DIN 30 670 ²¹ ANSI/AWWA C 215 ²²
Special Requirements for Application of Coating Over the Ditch	ANSI/AWWA C 20 ⁴⁰ NACE Standard RP0375 ¹¹ NACE Standard MR0274 ¹² ANSI/AWWA C 214 ¹³ ANSI/AWWA C 209 ¹⁴ <i>Peabody's Control of Pipeline Corrosion</i> ¹⁵ ANSI/AWWA C 213 ¹⁶ API RP 5L7 ¹⁷ CSA Z245.20M ¹⁸ NACE Standard RP0190 ¹⁹
Backfill Resistance	ASTM G 13 ³² ASTM G 14 ³³
Resistance to Thermal Effects	ASTM G 8 ²⁵ ASTM G 19 ²⁶ ASTM G 42 ²⁷ ASTM G 95 ²⁸ ASTM D 2304 ³⁹ ASTM D 2454 ⁴⁰ ASTM D 2485 ⁴¹

Table 4 Continued

Design and Construction Factor	Recommended Test Methods ^(A)
Suitability of Joint Coatings and Field Repairs	<i>Peabody's Control of Pipeline Corrosion</i> ¹⁵ ANSI/AWWA C 213 ¹⁶ API RP 5L7 ¹⁷ CSA Z245.20M ¹⁸ NACE Standard RP0190 ¹⁹ ASTM G 8 ²⁵ ASTM G 19 ²⁶ ASTM G 42 ²⁷ ASTM G 95 ²⁸ ASTM G 9 ²⁹ ASTM G 18 ⁴² ASTM G 55 ⁴³

^(A) No specific criteria are available. Comparative tests are recommended for use and evaluation as supplementary information only.

TABLE 5
Methods for Evaluating In-Service Field Performance of External Coatings

Title or Subject of Method	Reference	Basis for Rating
(1) Rate of Change in Current Required for Cathodic Protection	<i>Underground Corrosion</i> ³⁴	Comparison of initial current requirement with subsequent periodic determination of current requirement
(2) Inspection of Pipeline Coating	NACE Standard RP0274 ¹²	(a) With cathodic protection: no active corrosion found (b) Without cathodic protection: no new holidays showing active corrosion
(3) Cathodic Disbondment	ASTM G 8 ²⁵ ASTM G 19 ²⁶ ASTM G 42 ²⁷ ASTM G 95 ²⁸	Purpose is to obtain data relative to specific conditions for comparison with laboratory data

5.2.2 Inspection

5.2.2.1 Qualified personnel should keep every phase of the coating operation and piping installation under surveillance.

5.2.2.2 Surface preparation, primer application, coating thickness, temperature, bonding, and other specific requirements should be checked periodically, using suitable test procedures, for conformance to specifications.

5.2.2.3 The use of holiday detectors is recommended to detect coating flaws that would not be observed visually. The holiday detector should be operated in accordance with the manufacturer's instructions and at a voltage level appropriate to the electrical characteristics of the coating system.

5.2.3 Installation

5.2.3.1 Joints, fittings, and tie-ins must be coated with a material compatible with the existing coating.

5.2.3.2 Coating defects should be repaired.

5.2.3.3 Materials used to repair coatings must be compatible with the existing pipe coating.

5.2.3.4 The ditch bottom should be graded and free of rock or other foreign matter that could damage the external coating or cause electrical shielding. Under difficult conditions, consideration should be given to padding the pipe or the ditch bottom.

5.2.3.5 Pipe should be lowered carefully into the ditch to avoid external coating damage.

5.2.3.6 Care should be taken during backfilling so that rocks and debris do not strike and damage the pipe coating.

5.2.3.7 Care shall be exercised when using materials such as loose wrappers, nonconducting urethane foam, and rock shield around pipelines as protection against physical damage or for other purposes, because these materials may create an electrical shielding effect that would be detrimental to the effectiveness of cathodic protection.

5.2.3.8 When a pipeline comes above ground, it must be cleaned and externally coated, or jacketed with a suitable material, for the prevention of atmospheric corrosion.

5.3 Methods for Evaluating External Coating Systems

5.3.1 Established Systems Proven by Successful Use

5.3.1.1 Visual and electrical inspection of in-service pipeline coatings should be used to evaluate the performance of an external coating system. These inspections can be conducted wherever the pipeline is excavated or at bell holes made for inspection purposes.

5.3.2 Established or Modified Systems for New Environments

5.3.2.1 This method is intended for use when external coating systems will continue to be used and are qualified under Paragraph 5.3.1, but when application will be extended to new environments or when it is desired to revise a system to make use of new developments.

5.3.2.1.1 The use of applicable material requirements, material specifications, standards, and recommended practices for application, as given in Table 1, is recommended.

5.3.2.1.2 The use of applicable references in Table 2 is recommended unless previously covered in applicable references in Table 1.

5.3.3 New External Coating System Qualification

5.3.3.1 The purpose of this method is to qualify a new external coating material by subjecting it to laboratory tests appropriate for the intended service. After laboratory tests have been conducted and indicate that the external coating system appears to be suitable, application and installation are conducted in accordance with recommended practices. In-service field performance tests are made to confirm the success of the previous steps. The steps of the method are (1) laboratory tests, (2) application under recommended practices, (3) installation under recommended practices, and (4) in-service field performance tests. If good results are obtained after five years, only Steps 2 and 3 are required thereafter.

5.3.3.1.1 Applicable sections of Tables 3 and 4 are recommended for the initial laboratory test methods.

5.3.3.1.2 Applicable sections of Tables 1 and 2 are recommended for conditional use during Steps 2 and 3.

5.3.3.1.3 During a period of five years or more, the use of the evaluation methods given in Table 5, Item 1 or 2 are recommended. The test method in Item 3 may be used as a supplementary means for obtaining data for correlation with laboratory tests.

5.3.4 Method for Evaluating an External Coating System by In-Service Field Performance Only

5.3.4.1 The purpose of this method is to qualify an external coating system when none of the first three methods given in Paragraph 5.3 has been or will be used. It is intended that this method should be limited to minor pilot installations.

5.3.4.1.1 The use of at least one of the first two methods given in Table 5 is recommended on the basis of at least one investigation per year for five consecutive years.

Section 6: Criteria and Other Considerations for Cathodic Protection

6.1 Introduction

6.1.1 This section lists criteria and other considerations for cathodic protection that indicate, when used either separately or in combination, whether adequate cathodic protection of a metallic piping system has been achieved (see also Section 1, Paragraphs 1.2 and 1.4).

6.1.2 The effectiveness of cathodic protection or other external corrosion control measures can be confirmed by visual observation, by measurements of pipe wall thickness, or by use of internal inspection devices. Because such methods sometimes are not practical, meeting any criterion or combination of criteria in this section is evidence that adequate cathodic protection has been achieved. When excavations are made for

any purpose, the pipe should be inspected for evidence of corrosion and/or coating condition.

6.1.3 The criteria in this section have been developed through laboratory experiments and/or verified by evaluating data obtained from successfully operated cathodic protection systems. Situations in which a single criterion for evaluating the effectiveness of cathodic protection may not be satisfactory for all conditions may exist. Often a combination of criteria is needed for a single structure.

6.1.4 Sound engineering practices shall be used to determine the methods and frequency of testing required to satisfy these criteria.

6.1.5 Corrosion leak history is valuable in assessing the effectiveness of cathodic protection. Corrosion leak history by itself, however, shall not be used to determine whether adequate levels of cathodic protection have been achieved unless it is impractical to make electrical surveys.

6.2 Criteria

6.2.1 It is not intended that persons responsible for external corrosion control be limited to the criteria listed below. Criteria that have been successfully applied on existing piping systems can continue to be used on those piping systems. Any other criteria used must achieve corrosion control comparable to that attained with the criteria herein.

6.2.2 Steel and Cast Iron Piping

6.2.2.1 External corrosion control can be achieved at various levels of cathodic polarization depending on the environmental conditions. However, in the absence of specific data that demonstrate that adequate cathodic protection has been achieved, one or more of the following shall apply:

6.2.2.1.1 A negative (cathodic) potential of at least 850 mV with the cathodic protection applied. This potential is measured with respect to a saturated copper/copper sulfate reference electrode contacting the electrolyte. Voltage drops other than those across the structure-to-electrolyte boundary must be considered for valid interpretation of this voltage measurement.

NOTE: Consideration is understood to mean the application of sound engineering practice in determining the significance of voltage drops by methods such as:

6.2.2.1.1.1 Measuring or calculating the voltage drop(s);

6.2.2.1.1.2 Reviewing the historical performance of the cathodic protection system;

6.2.2.1.1.3 Evaluating the physical and electrical characteristics of the pipe and its environment; and

6.2.2.1.1.4 Determining whether or not there is physical evidence of corrosion.

6.2.2.1.2 A negative polarized potential (see definition in Section 2) of at least 850 mV relative to a saturated copper/copper sulfate reference electrode.

6.2.2.1.3 A minimum of 100 mV of cathodic polarization between the structure surface and a stable reference electrode contacting the electrolyte. The formation or decay of polarization can be measured to satisfy this criterion.

6.2.2.2 Special Conditions

6.2.2.2.1 On bare or ineffectively coated pipelines when long-line corrosion activity is of primary concern, the measurement of a net protective current at predetermined current discharge points from the electrolyte to the pipe surface, as measured by an earth current technique, may be sufficient.

6.2.2.2.2 In some situations, such as the presence of sulfides, bacteria, elevated temperatures, acid environments, and dissimilar metals, the criteria in Paragraph 6.2.2.1 may not be sufficient.

6.2.2.2.3 When a pipeline is encased in concrete or buried in dry or aerated high-resistivity soil, values less negative than the criteria listed in Paragraph 6.2.2.1 may be sufficient.

6.2.2.3 PRECAUTIONARY NOTES

6.2.2.3.1 The earth current technique is often meaningless in multiple pipe rights-of-way, in high-resistivity surface soil, for deeply buried pipe, in stray-current areas, or where local corrosion cell action predominates.

6.2.2.3.2 Caution is advised against using polarized potentials less negative than -850 mV for cathodic protection of pipelines when operating pressures and conditions are conducive to stress corrosion cracking (see references on stress corrosion cracking at the end of this section).

6.2.2.3.3 The use of excessive polarized potentials on externally coated pipelines should be avoided to minimize cathodic disbondment of the coating.

6.2.2.3.4 Polarized potentials that result in excessive generation of hydrogen should be avoided on all metals, particularly higher-strength steel, certain grades of stainless steel, titanium, aluminum alloys, and prestressed concrete pipe.

6.2.3 Aluminum Piping

6.2.3.1 The following criterion shall apply: a minimum of 100 mV of cathodic polarization between the structure surface and a stable reference electrode contacting the electrolyte. The formation or decay of this polarization can be used in this criterion.

6.2.3.2 PRECAUTIONARY NOTES

6.2.3.2.1 Excessive Voltages: Notwithstanding the minimum criterion in Paragraph 6.2.3.1, if aluminum is cathodically protected at voltages more negative than -1,200 mV measured between the pipe surface and a saturated copper/copper sulfate reference electrode contacting the electrolyte and compensation is made for the voltage drops other than those across the pipe-electrolyte boundary, it may suffer corrosion as the result of the buildup of alkali on the metal surface. A polarized potential more negative than -1,200 mV should not be used unless previous test results indicate that no appreciable corrosion will occur in the particular environment.

6.2.3.2.2 Alkaline Conditions: Aluminum may suffer from corrosion under high-pH conditions and application of cathodic protection tends to increase the pH at the metal surface. Therefore, careful investigation or testing should be done before applying cathodic protection to stop pitting attack on aluminum in environments with a natural pH in excess of 8.0.

6.2.4 Copper Piping

6.2.4.1 The following criterion shall apply: a minimum of 100 mV of cathodic polarization between the structure surface and a stable reference electrode contacting the electrolyte. The formation or decay of this polarization can be used in this criterion.

6.2.5 Dissimilar Metal Piping

6.2.5.1 A negative voltage between all pipe surfaces and a stable reference electrode contacting the electrolyte equal to that required for the protection of the most anodic metal should be maintained.

6.2.5.2 PRECAUTIONARY NOTE

6.2.5.2.1 Amphoteric materials that could be damaged by high alkalinity created by cathodic protection should be electrically isolated and separately protected.

6.3 Other Considerations

6.3.1 Methods for determining voltage drop(s) shall be selected and applied using sound engineering practices. Once determined, the voltage drop(s) may be used for correcting future measurements at the same location, providing conditions such as pipe and cathodic protection system operating conditions, soil characteristics, and external coating quality remain similar. (Note: Placing the reference electrode next to the pipe surface may not be at the pipe-electrolyte interface. A reference electrode placed at an externally coated pipe surface may not significantly reduce soil voltage drop in the measurement if the nearest coating holiday is remote from the reference electrode location.)

6.3.2 When it is impractical or considered unnecessary to disconnect all current sources to correct for voltage drop(s) in the structure-to-electrolyte potential measurements, sound engineering practices should be used to ensure that adequate cathodic protection has been achieved.

6.3.3 When feasible and practicable, in-line inspection of pipelines may be helpful in determining the presence or absence of pitting corrosion damage. Absence of external corrosion damage or the halting of its growth may indicate adequate external corrosion control. The in-line inspection technique, however, may not be capable of detecting all types of external corrosion damage, has limitations in its accuracy, and may report as anomalies items that are not external corrosion. For example, longitudinal seam corrosion and general corrosion may not be readily detected by in-line inspection. Also, possible thickness variations, dents, gouges, and external ferrous objects may be detected as corrosion. The appropriate use of in-line inspection must be carefully considered.

6.3.4 Situations involving stray currents and stray electrical gradients that require special analysis may exist. For additional information, see Section 9, "Control of Interference Currents."

6.4 Alternative Reference Electrodes

6.4.1 Other standard reference electrodes may be substituted for the saturated copper/copper sulfate

reference electrode. Two commonly used reference electrodes are listed below along with their voltage equivalent (at 25°C [77°F]) to -850 mV referred to a saturated copper/copper sulfate reference electrode:

6.4.1.1 Saturated KCl calomel reference electrode: -780 mV; and

6.4.1.2 Saturated silver/silver chloride reference electrode used in 25 ohm-cm seawater: -800 mV.

6.4.2 In addition to these standard reference electrodes, an alternative metallic material or structure may be used in place of the saturated copper/copper sulfate reference electrode if the stability of its electrode potential is ensured and if its voltage equivalent referred to a saturated copper/copper sulfate reference electrode is established.

Bibliography for Section 6

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Section 7: Design of Cathodic Protection Systems

7.1 Introduction

7.1.1 This section recommends procedures for designing cathodic protection systems that will provide effective external corrosion control by satisfying one or more of the criteria listed in Section 6 and exhibiting maximum reliability over the intended operating life of the systems.

7.1.2 In the design of a cathodic protection system, the following should be considered:

7.1.2.1 Recognition of hazardous conditions prevailing at the proposed installation site(s) and the selection and specification of materials and installation practices that ensure safe installation and operation.

7.1.2.2 Specification of materials and installation practices to conform to the latest editions of applicable codes, National Electrical Manufacturers Association (NEMA)⁽⁷⁾ standards, National

⁽⁷⁾ National Electrical Manufacturers Association (NEMA), 2101 L St., NW, Washington, DC 20037.

Electrical Code (NEC),⁽⁸⁾ appropriate international standards, and NACE standards.

7.1.2.3 Selection and specification of materials and installation practices that ensure dependable and economical operation throughout the intended operating life.

7.1.2.4 Selection of locations for proposed installations to minimize currents or earth potential gradients, which can cause detrimental effects on foreign buried or submerged metallic structures.

7.1.2.5 Cooperative investigations to determine mutually satisfactory solution(s) of interference problems (see Section 9).

7.1.2.6 Special consideration should be given to the presence of sulfides, bacteria, disbonded coatings, thermal insulating coatings, elevated temperatures, shielding, acid environments, and dissimilar metals.

7.1.2.7 Excessive levels of cathodic protection that can cause external coating disbondment and possible damage to high-strength steels as a result of hydrogen evolution should be avoided.

7.1.2.8 When amphoteric metals are involved, care should be taken so that high-pH conditions that could cause cathodic corrosion of the metal are not established.

7.2 Major objectives of cathodic protection system design include the following:

7.2.1 To provide sufficient current to the structure to be protected and distribute this current so that the selected criteria for cathodic protection are effectively attained;

7.2.2 To minimize the interference currents on neighboring underground structures (see Section 9);

7.2.3 To provide a design life of the anode system commensurate with the required life of the protected structure, or to provide for periodic rehabilitation of the anode system;

7.2.4 To provide adequate allowance for anticipated changes in current requirements with time;

7.2.5 To install anodes where the possibility of disturbance or damage is minimal; and

7.2.6 To provide adequate monitoring facilities to test and evaluate the system performance.

7.3 Information Useful for Design

7.3.1 Useful piping system specifications and information include the following:

7.3.1.1 Route maps and atlas sheets;

7.3.1.2 Construction dates;

7.3.1.3 Pipe, fittings, and other appurtenances;

7.3.1.4 External coatings;

7.3.1.5 Casings;

7.3.1.6 Corrosion control test stations;

7.3.1.7 Electrically isolating devices;

7.3.1.8 Electrical bonds; and

7.3.1.9 Aerial, bridge, and underwater crossings.

7.3.2 Useful information on piping system site conditions includes the following:

7.3.2.1 Existing and proposed cathodic protection systems;

7.3.2.2 Possible interference sources (see Section 9);

7.3.2.3 Special environmental conditions;

7.3.2.4 Neighboring buried metallic structures (including location, ownership, and corrosion control practices);

7.3.2.5 Structure accessibility;

7.3.2.6 Power availability; and

7.3.2.7 Feasibility of electrical isolation from foreign structures.

7.3.3 Useful information from field surveys, corrosion test data, and operating experience includes the following:

7.3.3.1 Protective current requirements to meet applicable criteria;

7.3.3.2 Electrical resistivity of the electrolyte;

7.3.3.3 Electrical continuity;

7.3.3.4 Electrical isolation;

7.3.3.5 External coating integrity;

7.3.3.6 Cumulative leak history;

⁽⁸⁾ National Fire Protection Association, Batterymarch Park, Quincy, MA 02269.

7.3.3.7 Interference currents;

7.3.3.8 Deviation from construction specifications; and

7.3.3.9 Other maintenance and operating data.

7.3.4 Field survey work prior to actual application of cathodic protection is not always required if prior experience or test data are available to estimate current requirements, electrical resistivities of the electrolyte, and other design factors.

7.4 Types of Cathodic Protection Systems

7.4.1 Galvanic Anode Systems

7.4.1.1 Galvanic anodes can be made of materials such as alloys of magnesium, zinc, or aluminum. The anodes are connected to the pipe, either individually or in groups. Galvanic anodes are limited in current output by the anode-to-pipe driving voltage and the electrolyte resistivity.

7.4.2 Impressed Current Anode Systems

7.4.2.1 Impressed current anodes can be of materials such as graphite, high-silicon cast iron, lead-silver alloy, precious metals, or steel. They are connected with an insulated cable, either individually or in groups, to the positive terminal of a direct-current (DC) source, such as a rectifier or generator. The pipeline is connected to the negative terminal of the DC source.

7.5 Considerations influencing selection of the type of cathodic protection system include the following:

7.5.1 Magnitude of protective current required;

7.5.2 Stray currents causing significant potential fluctuations between the pipeline and earth that may preclude the use of galvanic anodes;

7.5.3 Effects of cathodic protection interference currents on adjacent structures that may limit the use of impressed current cathodic protection systems;

7.5.4 Availability of electrical power;

7.5.5 Physical space available, proximity of foreign structures, easement procurement, surface conditions, presence of streets and buildings, river crossings, and other construction and maintenance concerns.

7.5.6 Future development of the right-of-way area and future extensions to the pipeline system;

7.5.7 Costs of installation, operation, and maintenance; and

7.5.8 Electrical resistivity of the environment.

7.6 Factors Influencing Design of Cathodic Protection Systems

7.6.1 Various anode materials have different rates of deterioration when discharging a given current density from the anode surface in a specific environment. Therefore, for a given current output, the anode life depends on the environment and anode material, as well as the anode weight and the number of anodes in the cathodic protection system. Established anode performance data may be used to calculate the probable deterioration rate.

7.6.2 Data on the dimensions, depth, and configuration of the anodes and the electrolyte resistivity may be used to calculate the resultant resistance to electrolyte of the anode system. Formulas and graphs relating to these factors are available in the literature and from manufacturers.

7.6.3 Design of galvanic anode systems should consider anode-to-pipe potential, electrolyte resistivity, current output, and in special cases, anode lead-wire resistance. A separate design for each anode or anode system may not be necessary.

7.6.4 Galvanic anode performance in most soils can be improved by using special backfill material. Mixtures of gypsum, bentonite, and anhydrous sodium sulfate are most commonly used.

7.6.5 The number of impressed current anodes required can be reduced and their useful life lengthened by the use of special backfill around the anodes. The most common materials are coal coke, calcined petroleum coke, and natural or manufactured graphite.

7.6.6 In the design of an extensive distributed-anode impressed current system, the voltage and current attenuation along the anode-connecting (header) cable should be considered. In such cases, the design objective is to optimize anode system length, anode spacing and size, and cable size in order to achieve efficient external corrosion control at the extremities of the protected structure.

7.6.7 When it is anticipated that entrapment of gas generated by anodic reactions could impair the ability of the impressed current groundbed to deliver the required current, suitable provisions should be made for venting the anodes. For the same current output of the system, an increase in the surface area of the special backfill material or an increase in the number of anodes may reduce gas blockage.

7.6.8 When it is anticipated that electroosmotic effects could impair the ability of the impressed current groundbed to deliver the required current output, suitable provisions should be made to ensure adequate soil moisture around the anodes. Increasing the number of impressed current anodes or increasing the

surface area of the special backfill materials may further reduce the electroosmotic effect.

7.7 Design Drawings and Specifications

7.7.1 Suitable drawings should be prepared to designate the overall layout of the piping to be protected and the location of significant items of structure hardware, corrosion control test stations, electrical bonds, electrical isolation devices, and neighboring buried or submerged metallic structures.

7.7.2 Layout drawings should be prepared for each impressed current cathodic protection installation, showing the details and location of the components of

the cathodic protection system with respect to the protected structure(s) and to major physical landmarks. These drawings should include right-of-way information.

7.7.3 The locations of galvanic anode installations should be recorded on drawings or in tabular form, with appropriate notes on anode type, weight, spacing, depth, and backfill.

7.7.4 Specifications should be prepared for all materials and installation practices that are to be incorporated in construction of the cathodic protection system.

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Section 8: Installation of Cathodic Protection Systems

8.1 Introduction

8.1.1 This section recommends procedures that will result in the installation of cathodic protection systems that achieve protection of the structure. The design considerations recommended in Sections 4 and 7 should be followed.

8.2 Construction Specifications

8.2.1 All construction work on cathodic protection systems should be performed in accordance with construction drawings and specifications. The construction specifications should be in accordance with recommended practices in Sections 4 and 7.

8.3 Construction Supervision

8.3.1 All construction work on cathodic protection systems should be performed under the surveillance of trained and qualified personnel to verify that the installation is in strict accordance with the drawings and specifications. Exceptions may be made only with the approval of qualified personnel responsible for external corrosion control.

8.3.2 All deviations from construction specifications should be noted on as-built drawings.

8.4 Galvanic Anodes

8.4.1 Inspection, Handling, and Storage

8.4.1.1 Packaged anodes should be inspected and steps taken to ensure that backfill material completely surrounds the anode. The individual container for the backfill material and anode should be intact. If individually packaged anodes are supplied in waterproof containers, the containers must be removed before installation. Packaged anodes should be kept dry during storage.

8.4.1.2 Lead wire must be securely connected to the anode. Lead wire should be inspected for assurance that it is not damaged.

8.4.1.3 Other galvanic anodes, such as the unpackaged "bracelet" or ribbon type, should be inspected to ensure that dimensions conform to design specifications and that any damage during handling does not affect application. If a coating is used on bands and the inner side of bracelet anode segments, it should be inspected and, if damaged, repaired before the anodes are installed.

8.4.2 Installing Anodes

8.4.2.1 Anodes should be installed according to construction specifications.

8.4.2.2 Packaged galvanic anodes should be backfilled with appropriately compacted material. When anodes and special chemical backfill are provided separately, anodes should be centered in special backfill, which should be compacted prior to backfilling. Care should be exercised during all operations so that lead wires and connections are not damaged. Sufficient slack should exist in lead wires to avoid strain.

8.4.2.3 When anodes in bracelet form are used, external pipe coating beneath the anode should be free of holidays. Care should be taken to prevent damage to the external coating when bracelet anodes are installed. After application of concrete (if used) to pipe, all coating and concrete should be removed from the anode surface. If reinforced concrete is used, there must be no metallic contact between the anode and the reinforcing mesh or between the reinforcing mesh and the pipe.

8.4.2.4 When a ribbon-type anode is used, it can be trenched or plowed in, with or without special chemical backfill as required, generally parallel to the section of pipeline to be protected.

8.5 Impressed Current Systems

8.5.1 Inspection and Handling

8.5.1.1 The rectifier or other power source should be inspected to ensure that internal connections are mechanically secure and that the unit is free of damage. Rating of the DC power source should comply with the construction specification. Care should be exercised in handling and installing the power source.

8.5.1.2 Impressed current anodes should be inspected for conformance to specifications concerning anode material, size, length of lead cable, anode lead connection, and integrity of seal. Care should be exercised to avoid cracking or damaging anodes during handling and installation.

8.5.1.3 All cables should be carefully inspected to detect defects in insulation. Care should be taken to avoid damage to cable insulation. Defects in the cable insulation must be repaired.

8.5.1.4 Anode backfill material should conform to specifications.

8.5.2 Installation Provisions

8.5.2.1 A rectifier or other power source should be installed so that the possibility of damage or vandalism is minimized.

8.5.2.2 Wiring to rectifiers shall comply with local and national electrical codes and requirements of the utility supplying power. An external disconnect switch should be provided in the AC circuit. A rectifier case shall be properly grounded.

8.5.2.3 On thermoelectric generators, a reverse-current device should be installed to prevent galvanic action between the anode bed and the pipe if the flame is extinguished.

8.5.2.4 Impressed current anodes can be buried vertically, horizontally, or in deep holes (see NACE Standard RP0572¹) as indicated in construction specifications. Backfill material should be installed to ensure that there are no voids around anodes. Care should be exercised during backfilling to avoid damage to the anode and cable.

8.5.2.5 The cable from the rectifier negative terminal to the pipe should be connected to the pipe as described in Paragraph 8.6. Cable connections to the rectifier must be mechanically secure and electrically conductive. Before the power source is energized, it must be verified that the negative cable is connected to the structure to be protected and that the positive cable is connected to the anodes. After the DC power source has been energized, suitable measurements should be made to verify that these connections are correct.

8.5.2.6 Underground splices on the header (positive) cable to the groundbed should be kept to a minimum. Connections between the header and anode cables should be mechanically secure and electrically conductive. If buried or submerged, these connections must be sealed to prevent moisture penetration so that electrical isolation from the environment is ensured.

8.5.2.7 Care must be taken during installation of direct-burial cable to the anodes (positive cable) to avoid damage to insulation. Sufficient slack should be left to avoid strain on all cables. Backfill material around the cable should be free of rocks and foreign matter that might cause damage to the insulation when the cable is installed in a trench. Cable can be installed by plowing if proper precautions are taken.

8.5.2.8 If insulation integrity on the buried or submerged header cable, including splices, is not maintained, this cable may fail because of corrosion.

8.6 Corrosion Control Test Stations, Connections, and Bonds (see Paragraph 4.5)

8.6.1 Pipe and test lead wires should be clean, dry, and free of foreign materials at points of connection when the connections are made. Connections of test lead wires to the pipe must be installed so they will remain mechanically secure and electrically conductive.

8.6.2 All buried or submerged lead-wire attachments should be coated with an electrically insulating material, compatible with the external pipe coating and wire insulation.

8.6.3 Test lead wires should be color coded or otherwise permanently identified. Wires should be installed with slack. Damage to insulation should be avoided and repairs made if damage occurs. Test leads should not be exposed to excessive heat and sunlight. Aboveground test stations are preferred. If test stations are flush with the ground, adequate slack should be provided within the test station to facilitate test connections.

8.6.4 Cable connections at bonds to other structures or across isolating joints should be mechanically secure, electrically conductive, and suitably coated. Bond connections should be accessible for testing.

8.7 Electrical Isolation

8.7.1 Inspection and electrical measurements should ensure that electrical isolation is adequate (see NACE Standard RP0286⁵).

Section 9: Control of Interference Currents

9.1 Introduction

9.1.1 This section recommends practices for the detection and control of interference currents. The mechanism and its detrimental effects are described.

9.2 Mechanism of Interference-Current Corrosion (Stray-Current Corrosion)

9.2.1 Interference-current corrosion on buried or submerged metallic structures differs from other causes of corrosion damage in that the direct current,

which causes the corrosion, has a source foreign to the affected structure. Usually the interfering current is collected from the electrolyte by the affected structure from a DC source not metallically bonded to the affected structure.

9.2.1.1 Detrimental effects of interference currents usually occur at locations where the currents transfer between the affected structures and the electrolyte.

9.2.1.2 Structures made of amphoteric metals such as aluminum and lead may be subject to corrosion damage from a buildup of alkalinity at or near the metal surface collecting interference currents.

9.2.1.3 Coatings may become disbonded at areas where voltage gradients in the electrolyte force current onto the affected structure. However, as the external coating becomes disbonded, a larger area of metal may be exposed, which would increase the demand for a cathodic protection current. This disbondment may create shielding problems.

9.2.2 The severity of external corrosion resulting from interference currents depends on several factors:

9.2.2.1 Separation and routing of the interfering and affected structures and location of the interfering current source;

9.2.2.2 Magnitude and density of the current;

9.2.2.3 Quality of the external coating or absence of an external coating on the structures involved; and

9.2.2.4 Presence and location of mechanical joints having high electrical resistance.

9.2.3 Typical sources of interference currents include the following:

9.2.3.1 Direct current: cathodic protection rectifiers, thermoelectric generators, DC electrified railway and transit systems, coal mine haulage systems and pumps, welding machines, and other direct current power systems;

9.2.3.2 Alternating current: AC power systems and AC electrified railway systems; and

9.2.3.3 Telluric current.

9.3 Detection of Interference Currents

9.3.1 During external corrosion control surveys, personnel should be alert for electrical or physical observations that could indicate interference from a foreign source such as the following:

9.3.1.1 Pipe-electrolyte potential changes on the affected structure caused by the foreign DC source;

9.3.1.2 Changes in the line current magnitude or direction caused by the foreign DC source;

9.3.1.3 Localized pitting in areas near or immediately adjacent to a foreign structure; and

9.3.1.4 Damage to external coatings in a localized area near an anode bed or near any other source of stray direct current.

9.3.2 In areas in which interference currents are suspected, appropriate tests should be conducted. All affected parties shall be notified before tests are conducted. Notification should be channeled through corrosion control coordinating committees, when they exist (see NACE Publication TPC 11⁸). Any one or a combination of the following test methods can be used.

9.3.2.1 Measurement of structure-electrolyte potentials with recording or indicating instruments;

9.3.2.2 Measurement of current flowing on the structure with recording or indicating instruments;

9.3.2.3 Development of beta curves to locate the area of maximum current discharge from the affected structure (see Appendix A); and

9.3.2.4 Measurement of the variations in current output of the suspected source of interference current and correlations with measurements obtained in Paragraphs 9.3.2.1 and 9.3.2.2.

9.4 Methods for Mitigating Interference Corrosion Problems

9.4.1 Interference problems are individual in nature and the solution should be mutually satisfactory to the parties involved. These methods may be used individually or in combination.

9.4.2 Design and installation of electrical bonds of proper resistance between the affected structures is a technique for interference control. The bond electrically conducts interference current from an affected structure to the interfering structure and/or current source.

9.4.2.1 Unidirectional control devices, such as diodes or reverse-current switches, may be required in conjunction with electrical bonds if fluctuating currents are present. These devices prevent reversal of current flow.

9.4.2.2 A resistor may be necessary in the bond circuit to control the flow of electrical current from the affected structure to the interfering structure.

9.4.2.3 The attachment of electrical bonds can reduce the level of cathodic protection on the interfering structure. Supplementary cathodic protection may then be required on the interfering structure to compensate for this effect.

9.4.2.4 A bond may not effectively mitigate the interference problem in the case of a cathodically protected bare or poorly externally coated pipeline that is causing interference on an externally coated pipeline.

9.4.3 Cathodic protection current can be applied to the affected structure at those locations at which the interfering current is being discharged. The source of cathodic protection current may be galvanic or impressed current anodes.

9.4.4 Adjustment of the current output from interfering cathodic protection rectifiers may resolve interference problems.

9.4.5 Relocation of the groundbeds of cathodic protection rectifiers can reduce or eliminate the pickup of interference currents on nearby structures.

9.4.6 Rerouting of proposed pipelines may avoid sources of interference current.

9.4.7 Properly located isolating fittings in the affected structure may reduce or resolve interference problems.

9.4.8 Application of external coating to current pick-up area(s) may reduce or resolve interference problems.

9.5 Indications of Resolved Interference Problems

9.5.1 Restoration of the structure-electrolyte potentials on the affected structure to those values that existed prior to the interference.

9.5.2 Measured line currents on the affected structure that show that the interference current is not being discharged to the electrolyte.

9.5.3 Adjustment of the slope of the beta curve to show that current discharge has been eliminated at the location of maximum exposure (see Appendix A).

Section 10: Operation and Maintenance of Cathodic Protection Systems

10.1 Introduction

10.1.1 This section recommends procedures and practices for energizing and maintaining continuous, effective, and efficient operation of cathodic protection systems.

10.1.1.1 Electrical measurements and inspection are necessary to determine that protection has been established according to applicable criteria and that each part of the cathodic protection system is operating properly. Conditions that affect protection are subject to change. Correspondingly, changes may be required in the cathodic protection system to maintain protection. Periodic measurements and inspections are necessary to detect changes in the cathodic protection system. Conditions in which operating experience indicates that testing and inspections need to be made more frequently than recommended herein may exist.

10.1.1.2 Care should be exercised in selecting the location, number, and type of electrical measurements used to determine the adequacy of cathodic protection.

10.1.1.3 When practicable and determined necessary by sound engineering practice, a detailed (close-interval) potential survey should be conducted to (a) assess the effectiveness of the

cathodic protection system; (b) provide base line operating data; (c) locate areas of inadequate protection levels; (d) identify locations likely to be adversely affected by construction, stray currents, or other unusual environmental conditions; or (e) select areas to be monitored periodically.

10.1.1.4 Adjustments to a cathodic protection system should be accompanied by sufficient testing to assure the criteria remain satisfied and to reassess interference to other structures or isolation points.

10.2 A survey should be conducted after each cathodic protection system is energized and/or adjusted to determine whether the applicable criterion or criteria from Section 6 have been satisfied.

10.3 The effectiveness of the cathodic protection system should be monitored annually. Longer or shorter intervals for monitoring may be appropriate, depending on the variability of cathodic protection factors, safety considerations, and economics of monitoring.

10.4 Inspection and tests of cathodic protection facilities should be made to ensure their proper operation and maintenance as follows:

10.4.1 All sources of impressed current should be checked at intervals of two months. Longer or shorter intervals for monitoring may be appropriate. Evidence

of proper functioning may be current output, normal power consumption, a signal indicating normal operation, or satisfactory cathodic protection levels on the pipe.

10.4.2 All impressed current protective facilities should be inspected annually as part of a preventive maintenance program to minimize in-service failure. Longer or shorter intervals for monitoring may be appropriate. Inspections may include a check for electrical malfunctions, safety ground connections, meter accuracy, efficiency, and circuit resistance.

10.4.3 Reverse-current switches, diodes, interference bonds, and other protective devices, whose failures would jeopardize structure protection, should be inspected for proper functioning at intervals of two months. Longer or shorter intervals for monitoring may be appropriate.

10.4.4 The effectiveness of isolating fittings, continuity bonds, and casing isolation should be evaluated during the periodic surveys. This may be accomplished by electrical measurements.

10.5 When pipe has been uncovered, it should be examined for evidence of external corrosion and, if externally coated, for condition of the external coating.

10.6 The test equipment used for obtaining each electrical value should be of an appropriate type. Instruments and related equipment should be maintained in good operating condition and checked for accuracy.

10.7 Remedial measures should be taken when periodic tests and inspections indicate that cathodic protection is no longer adequate. These measures may include the following:

10.7.1 Repair, replace, or adjust components of cathodic protection systems;

10.7.2 Provide supplementary facilities where additional cathodic protection is necessary;

10.7.3 Thoroughly clean and properly coat bare structures if required to attain cathodic protection;

10.7.4 Repair, replace, or adjust continuity and interference bonds;

10.7.5 Remove accidental metallic contacts; and

10.7.6 Repair defective isolating devices.

10.8 An electrical short circuit between a casing and carrier pipe can result in inadequate cathodic protection of the pipeline outside the casing due to reduction of protective current to the pipeline.

10.8.1 When a short results in inadequate cathodic protection of the pipeline outside the casing, steps must be taken to restore cathodic protection to a level required to meet the cathodic protection criterion. These steps may include eliminating the short between the casing and carrier pipe, supplementing cathodic protection, or improving the quality of the external coating on the pipeline outside the casing. None of these steps will ensure that external corrosion will not occur on the carrier pipe inside the casing; however, a shorted casing does not necessarily result in external corrosion of the carrier pipe inside the casing.

10.9 When the effects of electrical shielding of cathodic protection current are detected, the situation should be evaluated and appropriate action taken.

Section 11: External Corrosion Control Records

11.1 Introduction

11.1.1 This section describes external corrosion control records that will document in a clear, concise, workable manner, data that are pertinent to the design, installation, operation, maintenance, and effectiveness of external corrosion control measures.

11.2 Relative to the determination of the need for external corrosion control, the following should be recorded:

11.2.1 Corrosion leaks, breaks, and pipe replacements; and

11.2.2 Pipe and external coating condition observed when a buried structure is exposed.

11.3 Relative to structure design, the following should be recorded:

11.3.1 External coating material and application specifications; and

11.3.2 Design and location of isolating devices, test leads and other test facilities, and details of other special external corrosion control measures taken.

11.4 Relative to the design of external corrosion control facilities, the following should be recorded:

11.4.1 Results of current requirement tests;

11.4.2 Results of soil resistivity surveys;

11.4.3 Location of foreign structures; and

11.4.4 Interference tests and design of interference bonds and reverse-current switch installations.

11.4.4.1 Scheduling of interference tests, correspondence with corrosion control coordinating committees, and direct communication with the concerned companies.

11.4.4.2 Record of interference tests conducted, including location of tests, name of company involved, and results.

11.5 Relative to the installation of external corrosion control facilities, the following should be recorded:

11.5.1 Installation of cathodic protection facilities:

11.5.1.1 Impressed current systems:

11.5.1.1.1 Location and date placed in service;

11.5.1.1.2 Number, type, size, depth, backfill, and spacing of anodes;

11.5.1.1.3 Specifications of rectifier or other energy source; and

11.5.1.1.4 Cable size and type of insulation.

11.5.1.2 Galvanic anode systems:

11.5.1.2.1 Location and date placed in service;

11.5.1.2.2 Number, type, size, backfill, and spacing of anodes; and

11.5.1.2.3 Wire size and type of insulation.

11.5.2 Installation of interference mitigation facilities:

11.5.2.1 Details of interference bond installation:

11.5.2.1.1 Location and name of company involved;

11.5.2.1.2 Resistance value or other pertinent information; and

11.5.2.1.3 Magnitude and polarity of drainage current.

11.5.2.2 Details of reverse-current switch:

11.5.2.2.1 Location and name of companies;

11.5.2.2.2 Type of switch or equivalent device; and

11.5.2.2.3 Data showing effective operating adjustment.

11.5.2.3 Details of other remedial measures.

11.6 Records of surveys, inspections, and tests should be maintained to demonstrate that applicable criteria for interference control and cathodic protection have been satisfied.

11.7 Relative to the maintenance of external corrosion control facilities, the following information should be recorded:

11.7.1 Maintenance of cathodic protection facilities:

11.7.1.1 Repair of rectifiers and other DC power sources; and

11.7.1.2 Repair or replacement of anodes, connections, wires, and cables.

11.7.2 Maintenance of interference bonds and reverse current switches:

11.7.2.1 Repair of interference bonds; and

11.7.2.2 Repair of reverse-current switches or equivalent devices.

11.7.3 Maintenance, repair, and replacement of external coating, isolating devices, test leads, and other test facilities.

11.8 Records sufficient to demonstrate the evaluation of the need for and the effectiveness of external corrosion control measures should be maintained as long as the facility involved remains in service. Other related external corrosion control records should be retained for such a period that satisfies individual company needs.

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Appendix A—Interference Testing

A beta curve is a plot of dynamic (fluctuating) interference current or related proportional voltage (ordinate) versus values of corresponding structure-to-soil potentials at a selected location on the affected structure (abscissa). If the correlation is reasonably linear, the plot will indicate whether the affected structure is receiving or discharging current at the location where the structure-to-soil potential was measured. Dynamic interference investigation involves

many beta curve plots to search for the point of maximum interference-current discharge. Interference is resolved when the correlation of maximum current discharge has been changed to a correlation that shows that current pickup is being achieved in the exposure area by the corrective measures taken. These corrective measures may be accomplished by metallic bonding or other interference control techniques.

Appendix B—Method for Determining Probable Corrosion Rate and Costs of Maintaining Service

Maintenance of a piping system may include repairing corrosion leaks and reconditioning or replacing all or portions of the system.

In order to make estimates of the costs involved, it is necessary to determine the probability of corrosion or the rate at which corrosion is proceeding. The usual methods of predicting the probability or rate of corrosion are as follows:

- (a) Study of corrosion history on the piping system in question or on other systems of the same material in the same general area or in similar environments. Cumulative leak-frequency curves are valuable in this respect.
- (b) Study of the environment surrounding a piping system: resistivity, pH, and composition. Redox potential tests may also be used to a limited extent. Once the nature of the environment has been determined, the probable corrosiveness is estimated by reference to actual corrosion experience on similar metallic structures where environmental conditions are similar. Consideration of

possible environmental changes such as might result from irrigation, spillage of corrosive substances, pollution, and seasonal changes in soil moisture content should be included in such a study.

- (c) Investigation for corrosion on a piping system by visual inspection of the pipe and/or by instruments that mechanically or electrically inspect the condition of the pipe. Condition of the piping system should be carefully determined and recorded each time a portion of the line is excavated for any reason.
- (d) Maintenance records detailing leak locations, soil studies, structure-to-electrolyte potential surveys, surface potential surveys, line current studies, and wall thickness surveys used as a guide for locating areas of maximum corrosion.
- (e) Statistical treatment of available data.
- (f) Results of pressure testing. Under certain conditions, this may help to determine the existence of corrosion.

Appendix C—Contingent Costs of Corrosion

In addition to the direct costs that result from corrosion, contingent costs include:

- (a) Public liability claims;
- (b) Property damage claims;
- (c) Damage to natural facilities, such as municipal or irrigation water supplies, forests, parks, and scenic areas;
- (d) Cleanup of product lost to surroundings;
- (e) Plant shutdown and startup costs;
- (f) Cost of lost product;
- (g) Loss of revenue through interruption of service;
- (h) Loss of contract or goodwill through interruption of service; and
- (i) Loss of reclaim or salvage value of piping system.

Appendix D—Costs of Corrosion Control

The usual costs for protecting buried or submerged metallic structures are for complete or partial cathodic protection or for external coatings supplemented with cathodic protection. Other corrosion control costs include:

- (a) Relocation of piping to avoid known corrosive conditions (this may include installing lines above ground);
- (b) Reconditioning and externally coating the piping system;
- (c) Use of corrosion-resistant materials;
- (d) Use of selected or inhibited backfill;
- (e) Electrical isolation to limit possible galvanic action; and
- (f) Correction of conditions in or on the pipe that might accelerate corrosion.

RP0169-2002

ISBN 1-57590-035-1

NACE International

Standard Recommended Practice

Corrosion Control of Underground Storage Tank Systems by Cathodic Protection

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Revised 2002-04-06
Revised February 1995
Approved March 1985
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ISBN 1-57590-143-9
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Foreword

This standard recommended practice presents procedures and practices for effective control of external corrosion on underground storage tank (UST) systems by cathodic protection (CP). It is intended to be used by competent corrosion professionals as a reference for corrosion control of buried metallic underground storage tanks including those used to contain oil, gas, and water using CP. Specifically addressed is CP of:

- (a) Existing bare and coated mild steel tanks;
- (b) New coated mild steel tanks;
- (c) Metallic piping and flexible connectors; and
- (d) Other metallic components.

For accurate and correct application of this standard, this standard must be used in its entirety. Using or referring to only specific paragraphs or sections can lead to misinterpretation and misapplication of the recommendations and practices contained in the standard.

This standard was originally published in 1985 by Task Group T-10A-14 as "Control of External Corrosion on Metallic Buried, Partially Buried, or Submerged Liquid Storage Systems." The standard was revised in 1995 by Task Group T-10A-14 on Corrosion Control of Underground Storage Tank Systems, a component of Unit Committee T-10A on Cathodic Protection. It was revised in 2001 by TG 011 on Corrosion Control of Underground Storage Tank Systems by Cathodic Protection. Task Group 011 is administered by Specific Technology Group (STG) 35 on Pipelines, Tanks, and Well Casings and is sponsored by STG 03 on Protective Coating and Linings—Immersion/Buried and STG 05 on Cathodic/Anodic Protection. This standard is issued by NACE International under the auspices of STG 35 on Pipelines, Tanks, and Well Casings.

In NACE standards, the terms *shall*, *must*, *should*, and *may* are used in accordance with the definitions of these terms in the *NACE Publications Style Manual*, 4th ed., Paragraph 7.4.1.9. *Shall* and *must* are used to state mandatory requirements. *Should* is used to state that which is considered good and is recommended but is not absolutely mandatory. *May* is used to state that which is considered optional.

**NACE International
Standard
Recommended Practice**

**Corrosion Control of Underground Storage Tanks Systems
by Cathodic Protection**

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Section 1: General

1.1 Introduction

1.1.1 This standard is intended to serve as a guide for establishing minimum requirements for the control of external corrosion on UST systems that are buried, partially buried, or in contact with the soil.

1.1.2 This standard does not designate specific practices for every situation because the complexity of some environmental conditions in which systems are buried precludes standardization of corrosion control practices.

1.1.3 This standard does not include corrosion control methods based on chemical control of the environment, internal linings, or the use of tank construction materials other than mild steel.

1.1.4 This standard does not override applicable safety codes and should not be used to infringe on the

primary requirement of protecting personnel, the environment, and equipment. In any situation, the corrosion protection design for underground structures should incorporate all requirements of any applicable codes, standards, and regulations as determined by authorities having jurisdiction.

1.1.5 The provisions of this standard shall be applied under the responsible direction of competent individuals. Such individuals must either be registered professional engineers, NACE International Certified Corrosion Specialists or CP Specialists, or individuals qualified by professional education and related practical experience. All of the above individuals must be able to demonstrate suitable experience in corrosion control of UST systems.

1.1.6 Deviation from this standard may be warranted in specific situations provided the objectives expressed in this standard have been achieved.

Section 2: Definitions

Anode: The electrode of an electrochemical cell at which oxidation occurs. Electrons flow away from the anode in the external circuit. Corrosion usually occurs and metal ions enter the solution at the anode.

Cathode: The electrode of an electrochemical cell at which reduction is the principal reaction. Electrons flow toward the cathode in the external circuit.

Cathodic Disbondment: The destruction of adhesion between a coating and the coated surface caused by products of a cathodic reaction.

Cathodic Polarization: The change of the electrode potential in the active (negative) direction caused by current across the electrode/electrolyte interface. (See *Polarization*.)

Cathodic Protection (CP): A technique to reduce the corrosion of a metal surface by making that surface the cathode of an electrochemical cell.

Continuity Bond: A connection, usually metallic, that provides electrical continuity between structures that can conduct electricity.

Corrosion: The deterioration of a material, usually a metal, that results from a reaction with its environment.

Corrosion Potential (E_{corr}): The potential of a corroding surface in an electrolyte relative to a reference electrode under open-circuit conditions (also known as *rest potential*, *open-circuit potential*, or *freely corroding potential*).

Current Density: The current to or from a unit area of an electrode surface.

Dielectric Coating: A coating that does not conduct electricity.

Electrical Isolation: The condition of being electrically separated from other metallic structures or the environment.

Electrochemical Cell: A system consisting of an anode and a cathode immersed in an electrolyte so as to create an electrical circuit. The anode and cathode may be different metals or dissimilar areas on the same metal surface.

Electrode Potential: The potential of an electrode in an electrolyte as measured against a reference electrode. (The electrode potential does not include any resistance losses in potential in either the solution or the external circuit. It represents the reversible work to move a unit of charge from the electrode surface through the electrolyte to the reference electrode.)

Electrolyte: A chemical substance containing ions that migrate in an electric field. For the purposes of this standard, electrolyte refers to the soil or liquid adjacent to and in contact with a buried or submerged metallic UST system, including the moisture and other chemicals contained therein.

Electrolytic Corrosion: Corrosion caused by an external source of direct current.

Foreign Structure: Any metallic structure that is not intended as part of a system under CP.

Galvanic Anode: A metal that provides sacrificial protection to another metal that is more noble when electrically coupled in an electrolyte. This type of anode is the electron source in one type of CP.

Galvanic Series: A list of metals and alloys arranged according to their corrosion potentials in a given environment.

Groundbed: One or more anodes installed below the earth's surface for the purpose of supplying CP.

Holiday: A discontinuity in a protective coating that exposes unprotected surface to the environment.

Impressed Current: An electric current supplied by a device employing a power source that is external to the electrode system. (An example is direct current for CP.)

Insulating Coating System: All components comprising the protective coating, the sum of which provides effective electrical isolation of the coated structure.

Interference Bond: A metallic connection designed to control electrical current interchange between metallic systems.

IR Drop: The voltage across a resistance in accordance with Ohm's Law.

Isolation: See *Electrical Isolation*.

Net Driving Potential: The difference between the cathode potential and the anode potential in a galvanic circuit.

Polarization: The change from the open-circuit potential as a result of current across the electrode/electrolyte interface. In this standard, polarization is considered to be the change of potential of a metal surface resulting from the passage of current directly to or from an electrode.

Polarized Potential: The potential across the structure/electrolyte interface that is the sum of the corrosion potential and the cathodic polarization.

Potential Gradient: A change in the potential with respect to distance, expressed in millivolts per unit of distance.

Reference Electrode: An electrode whose open-circuit potential is constant under similar conditions of measurement, which is used for measuring the relative potentials of other electrodes.

Stray Current: Current through paths other than the intended circuit.

Stray-Current Corrosion: Corrosion resulting from current through paths other than the intended circuit, e.g., by any extraneous current in the earth.

Structure-to-Electrolyte Potential (also structure-to-soil potential or pipe-to-soil potential): The potential difference between a buried metallic structure and the electrolyte that is measured with a reference electrode in contact with the electrolyte.

Structure-to-Structure Potential: The difference in voltage between metallic structures in a common electrolyte.

Tank-to-Soil Potential (also tank-to-electrolyte potential): The potential difference between the tank metallic surface and the electrolyte that is measured with reference to an electrode in contact with the electrolyte.

Underground Storage Tank (UST) System: The equipment and facility constructed, maintained, or used for underground storage of products including tanks, piping, pumps, and appurtenances associated with filling, storage, and dispensing of the stored products.

Section 3: Cathodic Protection of New UST Systems

3.1 General

3.1.1 There are three basic types of CP available for new UST systems:

- (a) Factory-fabricated galvanic anode systems.
- (b) Field-installed galvanic anode systems.

(c) Field-installed impressed current systems.

3.1.2 The recommended practices with respect to field-installed systems are similar to those for existing UST systems described in Section 4.

3.2 Factory-Fabricated CP Systems

3.2.1 Single- and Double-Wall Tanks

3.2.1.1 Factory-fabricated galvanic anode CP systems are available for new USTs. The design and specifications for the factory-fabricated galvanic anode CP systems consider three important factors:

- (a) the galvanic anodes;
- (b) a dielectric coating; and
- (c) electrical isolation.

The components are designed together as a system to achieve corrosion protection for various tank sizes and most site conditions. Bonding of this system to other structures may violate the manufacturer's warranty.

3.2.2 Anodes

3.2.2.1 Packaged zinc or magnesium anodes are used for factory-fabricated systems. Aluminum anodes usually are not effective in underground applications. The size and number of anodes required to protect a tank from corrosion is predetermined by calculations based on the desired design life, the tank surface area, the quality of the coating, anode type, anode size, and the range of soil resistivity in which it is anticipated that the tank will be installed.

3.2.2.2 The anodes can be attached directly to the tank or wired through a test station to the tank. The type of anode used is determined by site conditions and operational factors. Zinc is the most common type of anode used for factory-fabricated systems. Magnesium anodes are more effective in high soil resistivities and shall be used on tanks where the anode temperature exceeds 49°C (120°F).

3.3 Piping for New USTs

3.3.1 Corrosion protection of all underground piping associated with the UST system can be achieved through a combination of material selection, system design, and coatings.

3.3.2 Piping within a secondary containment piping system may require other corrosion control methods in lieu of CP.

3.3.3 Several design parameters to be considered in selecting materials include:

- (a) compatibility with the environment;
- (b) compatibility with the product to be contained; and
- (c) pressure and temperature.

3.3.4 Metallic Piping

3.3.4.1 Metallic piping in contact with an electrolyte shall be protected from external corrosion through the application of coatings and CP.

3.3.4.2 When available, factory-applied coatings are preferred. The following NACE International standards may be helpful:

- (a) RP0190;¹
- (b) RP0185;²
- (c) RP0375;³ and
- (d) MR0274.⁴

3.3.4.3 All metallic components to be cathodically protected should be made electrically continuous. When using galvanic anode CP, all metallic components to be protected should be electrically isolated from all other metallic components.

3.3.4.4 Metal piping with mechanical joints may require bonding to ensure electrical continuity.

3.3.4.5 Recommendations for CP monitoring, including facilities and configurations, are given in Section 8.

3.3.4.6 Metallic secondary containment systems exposed to an electrolyte should be cathodically protected.

3.3.4.7 CP systems shall be designed to mitigate any adverse effects from stray current on foreign metallic structures within the influence of the CP system.

3.3.5 Nonmetallic Piping

3.3.5.1 Nonmetallic piping cannot be protected by CP; however, any metallic components of the product piping system that are exposed to soil shall be protected.

3.3.5.2 Materials selection should assure product compatibility not only with the basic pipe material, but also with any adhesives or joint compounds.

3.3.6 Flexible Connectors

3.3.6.1 Flexible connectors are used on rigid piping systems to accommodate pipe movement. These connections, depending on materials of construction, may create dissimilar metal couples in buried applications.

3.3.6.2 Flexible connectors may not provide electrical continuity. Verification and bonding may be required based on the system design.

3.3.6.3 All metallic components of the connection in contact with the electrolyte shall be cathodically protected. (Protection of flexible connectors is often overlooked in nonmetallic piping systems.)

3.3.6.4 Factory-fabricated CP systems are available for flexible connectors.

3.3.7 All corrosion protection systems should be monitored in accordance with Section 8 on Operation and Maintenance.

3.4 Coatings

3.4.1 A high-quality dielectric coating should be applied to a properly prepared surface of the exterior areas of the UST including anode connections, attachments, and lifting lugs. Crevice or corner areas that restrict coating coverage should be seal welded prior to coating.

3.4.2 Any type of coating used on a steel tank must have high dielectric properties. The purpose of a dielectric coating is to isolate the tanks electrically from the environment while reducing demands on the CP system. Other properties necessary in a dielectric coating are resistance to environmental fluids and the product being stored, impact/abrasion resistance, adhesion, and resistance to cathodic disbondment.

3.4.2.1 Three types of dielectric coatings commonly used on steel USTs are polyurethanes, epoxies, and reinforced plastics. Performance of these coatings should conform to a recognized industry standard such as:

- (a) STI⁽¹⁾ T871,⁵ or
- (b) UL⁽²⁾ 1746,⁶ Part 1, Section 10.

3.4.2.2 When flaws, damage, and degradation occur on coatings, these damaged areas must be repaired in accordance with manufacturer's specifications.

3.5 Electrical Isolation

3.5.1 A factory-fabricated cathodically protected steel tank is usually electrically isolated from all other structures (product and vent piping, hold-down straps, liquid-level monitoring systems, interstitial space monitors, conduit lines, etc.) for the CP system to perform as designed. Electrical isolation of a factory-fabricated cathodically protected UST is required because the CP system design capacity is sufficient only for the tank. Isolation devices are normally installed at the manufacturing plant to eliminate

installation errors and to be compatible with the product being stored. The device used to ensure isolation is dependent on the type of connection being made to the tank. Electrical isolation devices should only be used within their temperature and pressure limitations.

3.5.1.1 Dielectric bushings are used for threaded connections in nonpressure tanks. These bushings shall be as specified in UL Standard 1746, Part I, Section 11, and STI-P3,⁷ or meet equivalent requirements.

3.5.1.2 Flanged connections are used when conditions preclude the use of dielectric bushings. Flange isolation kits should be used if flanged connections are to be made in the field.

3.5.1.3 If hold-down straps are to be used, effective isolation material shall be used between the strap and tank surface.

3.5.2 The isolation should be verified after installation is completed but before backfilling and final paving or grading.

3.6 Backfill Requirements

3.6.1 The backfill shall be a homogeneous material that is compatible with the coating and CP system. The backfill material shall be free of large rocks, trash, debris, ice, and other nonhomogeneous materials.

3.6.2 The CP design shall consider situations in which protective current flow is obstructed by geologic conditions or the presence of other structures.

3.7 Miscellaneous

3.7.1 Tanks are often anchored to prevent buoyant forces from floating the tanks. Anchor materials shall consist of flat straps that are isolated from the tank surface with a dielectric insulating material. Wire cable or steel round bars should not be used because point-of-contact damage to the coating can occur. Corrosion control of the strap components shall be considered.

3.7.2 Each protected UST system should have the following:

- (a) a dedicated test lead wire connected to the structure;
- (b) access to the electrolyte for portable reference electrode tests; and
- (c) accessible connection points for all permanently installed monitoring devices.

⁽¹⁾ Steel Tank Institute (STI), 570 Oakwood Rd., Lake Zurich, IL 60047.

⁽²⁾ Underwriters Laboratories Inc. (UL), 333 Pfingsten Rd., Northbrook, IL 60062.

Section 4: Cathodic Protection of Existing UST Systems

4.1 Prior to initiation of the field testing necessary for design of CP, it is advisable to assemble information concerning the history of the tank(s) to be protected. This information generally falls into two groups: physical description and operating history. Although all information may not be available for every tank, it is important to obtain as much as possible. This information can save field investigation time, resulting in a more cost-effective system, and can help to avoid an ineffective design.

4.2 Physical Description

4.2.1 Size, Configuration, and Condition: The type of CP system and the amount of cathodic current required to protect the tanks and piping depends on the surface area, coating quality of the structures, and the properties of the electrolyte. The configuration of the tanks and piping and their location with respect to other structures at the site may also affect the type of system selected.

4.2.2 Materials of Construction: Knowledge of the materials and construction of the tanks, piping, and related facilities is required to assess the probable corrosion mechanisms affecting the facilities and to determine which structures will require CP. The materials of construction include any buried portion of the tank system (e.g., valves, fittings, tank pads, straps, anchors, foundations, ground rods, cables, monitoring devices, the tank, and the piping). The use of different metals for the various components can accelerate corrosion on an unprotected UST system and can affect the current required for CP. The existence and condition of coatings on the metallic components also have a significant influence on the design of the CP system.

4.2.3 Electrical Continuity: The design and operation of CP systems are dependent on the extent of electrical continuity of the underground metallic structures. The existence of intentional bonding, grounding, or electrical isolation of underground metallic structures should be considered. Unnecessary electrical grounds should be considered for removal. The method of electrical joining of piping, tanks, and associated underground structures, including conduits, may affect the CP design.

4.2.4 Other Underground Structures: The presence of additional underground structures unrelated to the tank system can affect the feasibility, type, and capacity of the proposed CP system.

4.2.5 Pavement: The presence and thickness of pavement at the site can affect both the operation of the CP system and the cost of installation. The location, type, age, and probable repaving schedule are of interest to the designer. The presence of other significant site improvements must be considered.

4.3 Integrity Assurance

4.3.1 The operating history of the UST system, including the date of installation and as-built drawings, provides important information for evaluation.

4.3.2 The results of tightness testing, internal inspection, or other industry recognized methods of integrity assurance should be analyzed (see API⁽³⁾ RP 1631⁸ for additional information).

4.3.3 The leak history of the UST may influence the feasibility of the retrofit CP system. The date, location, and type of each leak should be assessed.

4.3.4 Repairs or replacements of UST system components should be analyzed as to their effect on the system's probability for corrosion or on the operation and effectiveness of the retrofit CP system. The reason for repairs, replacements, or system modifications, as well as the materials and methods used, should be analyzed.

4.3.5 Operating data of any previous CP system for the UST, including the type of CP system (galvanic or impressed current), the date of installation, the type, size, and placement of anodes, and the level of protection, should be reviewed.

4.4 On-Site Testing

4.4.1 All test methods shall be in accordance with applicable engineering standards.

4.4.2 Soil borings may be performed. The following measurements should be recorded as each test hole progresses:

- (a) tank-to-soil potential profile; and
- (b) soil resistivity profile.

⁽³⁾ American Petroleum Institute (API), 1220 L Street NW, Washington, DC 20005.

4.4.3 When required, soil samples should be extracted from the bore holes and placed in sealed sample containers for analysis to include:

- (a) resistivity;
- (b) pH;
- (c) sulfide ion concentration;
- (d) chloride ion concentration; and
- (e) moisture content.

4.4.4 Tests that should be included in the investigation for the evaluation of corrosion on USTs and the design of CP systems include the following:

4.4.4.1 Soil Resistivity: Low-resistivity soils are usually more corrosive than high-resistivity soils; however, serious corrosion can also be associated with high-resistivity soils, particularly when the soil composition is not uniform. Variations in resistivity indicate variations in soil composition, which is conducive to galvanic corrosion. Accepted soil resistivity tests include the Wenner four-pin,⁹ soil box, and single-probe methods.

4.4.4.2 Structure-to-Soil Potential

4.4.4.2.1 Structure-to-soil potentials are used to evaluate the corrosion activity associated with UST systems. If properly interpreted and correlated with other measurements, structure-to-soil potentials should give an indication of the severity of both galvanic and electrolytic corrosion cells.

4.4.4.2.2 Measurements should be taken with a high-input impedance voltmeter.

4.4.4.2.3 Saturated copper/copper sulfate reference electrodes (CSEs) are used for underground corrosion testing because they are stable, rugged, and yield reproducible results. Electrode placement is important when collecting the data. Proper notation of electrode location for each reading is required. When test borings are made, the reference electrode should be placed near the tank/soil interface. Typically, the test hole is drilled 0.3 m (1 ft) from the edge of the tank to a depth of 0.6 m (2 ft) below the tank. Tank-to-soil potentials are recorded at various depths to establish the potential profile from grade level to below the tank.

4.4.4.3 Stray direct current (DC) can emanate from the operation of DC transit systems, CP rectifiers, DC welding equipment, and DC motors.

When discharged from the surface of a steel tank, these currents consume approximately 9 kg/A-y (20 lb/A-y) of metal. Concentrated electrolytic corrosion can cause rapid deterioration of UST systems. The presence of stray current is detected through the use of structure-to-soil potential, current flow, and potential gradient measurements.

4.4.4.4 Current requirement: Tests simulating the effects of a permanently installed CP system can be evaluated to determine the DC requirements for protection. Temporary CP anodes are installed in the surrounding soil and connected to the positive terminal of a DC power source; the negative terminal of the power source shall be connected to the UST system under test. Structure-to-soil potentials are then measured at accessible locations. Data, including the polarization effects over time, can then be extrapolated to determine the requirements for CP current. The status of electrical isolation of the structure under study is considered in the evaluation of current requirements testing.

4.4.4.5 Electrical continuity testing is necessary to determine whether all tanks and piping are electrically continuous and whether continuity with other structures exists. Temporary anodes shall be energized by a DC power source that is cycled "on" and "off." A CSE or other suitable reference electrode shall be placed in a stationary position, and structure-to-soil potentials recorded with the structure connection moved from one location to the next. At each point of structure connection, both "on" and "instant off" potential readings can be observed with the cycling of the DC power source. The CSE must remain at the same location for the duration of each continuity test. Electrical continuity is indicated when the potential measurements and changes in potential measurements with the applied current are approximately equal, regardless of the point of connection to the structure. Differences in the structure-to-soil potentials and changes in potential indicate the lack of electrical continuity between the points of contact.

4.5 Laboratory Testing

4.5.1 pH: For a given resistivity, acid soils (pH less than 7) are more conducive to ferrous corrosion. At pH values below 4, the rate of corrosion accelerates rapidly. At pH values above 10, the environment tends to passivate the steel. All pH testing should be done in accordance with ASTM⁽⁴⁾ G 51.¹⁰

⁽⁴⁾ ASTM International (ASTM), 100 Barr Harbor Dr., West Conshohocken, PA 19428-2959.

4.5.2 Chloride Ion: Chloride ions are depassivating agents and cause pitting corrosion. ASTM D 512¹¹ is used to measure chloride ion concentration.

4.5.3 Sulfide Ion: The presence of sulfide ions in the soil indicates anaerobic conditions. Under these conditions, sulfate-reducing bacteria can greatly accelerate the rate of corrosion. The test procedure shall satisfy the requirements of Method 4500¹² for sulfide, sulfite, and sulfate, and Method 9240 D¹³ for sulfate-reducing bacteria.

4.5.4 Moisture Content

4.5.4.1 The moisture content is a significant parameter in determining the corrosiveness of a soil environment. When soil samples are collected, they shall be immediately sealed in sample containers to prevent evaporation and contamination. The moisture content of the samples should be determined using ASTM D 2216.¹⁴

4.5.4.2 Test borings allow for a determination of the variations in moisture content with depth. When encountered, the depth of the water table should also be noted on the boring logs.

4.6 Data Analysis

4.6.1 This subsection outlines the analysis that may be performed prior to designing a CP system to protect existing USTs. The results of tests determine the extent and type of CP system to be installed. The analysis of these data is valuable in determining unusual conditions (e.g., stray current, dissimilar metals, and large corrosion cells), native-state characteristics needed for commissioning the completed CP system, and electrical continuity.

4.6.2 Results of other tests (soil resistivity, structure-to-soil potential, stray current, current requirements, electrical continuity, pH, chloride ion, sulfide ion, moisture, etc.) aid in determining the type and extent of the CP system to be considered. Interpretation of these results should consider seasonal variations.

4.6.3 Investigation of all previous repairs to the UST shall be performed to determine the probability of severe corrosion damage to these facilities. All necessary repairs shall be completed before the installation of a CP system is considered (see API RP 1631⁸ for additional information).

4.6.4 All UST systems may not be good candidates for a CP system. If tests reveal critically damaged components, consideration should be given to UST system replacement or removal from service.

Section 5: Criteria for Cathodic Protection

5.1 General

5.1.1 This section lists criteria for cathodic protection which, when complied with either separately or collectively, indicate that adequate cathodic protection of a metallic UST system has been achieved.

5.1.2 The objective of using CP is to control the corrosion of UST systems.

5.1.3 The selection of a particular criterion depends, in part, on prior experience with similar structures and environments in which the criterion has been used successfully.

5.1.4 The criteria in Paragraph 5.2 were developed through laboratory experiment or were determined empirically by evaluating data obtained from successfully operated CP systems. It is not intended that people responsible for corrosion control be limited to these criteria if it can be demonstrated by other means that the control of corrosion has been achieved.

5.1.5 Voltage measurements on UST systems are to be made with the reference electrode located on the electrolyte surface as close as possible to the UST

system. Consideration must be given to voltage (IR) drops other than those across the structure/electrolyte boundary, the presence of dissimilar metals, and the influence of other structures that may interfere with valid interpretation of voltage measurements. All readings shall be taken with reference electrodes that are in contact with the electrolyte. Readings shall not be taken through concrete or asphalt. Soil contact may be established through at-grade openings, by drilling a small hole in the concrete or asphalt, or by contacting a seam of soil between concrete and asphalt.

NOTE: Consideration is understood to mean the application of sound engineering practice in determining the significance of voltage drops by methods such as:

- (a) Measuring or calculating the voltage drop(s).
- (b) Reviewing the historical performance of the CP system.
- (c) Evaluating the physical and electrical characteristics of the UST system and its environment.
- (d) Determining whether or not there is physical evidence of corrosion.

5.2 Criteria for Steel Structures

5.2.1 Corrosion control can be achieved at various levels of cathodic polarization depending on the environmental condition. However, in the absence of data that demonstrate adequate CP has been achieved, one or more of the following shall apply:

5.2.1.1 A negative (cathodic) potential of at least 850 mV with the CP applied. This potential is measured with respect to a CSE contacting the electrolyte. Voltage drops other than those across the structure/electrolyte boundary must be considered for valid interpretation of this voltage measurement.

5.2.1.2 A negative polarized potential (see definition in Section 2) of at least 850 mV relative to a CSE.

5.2.1.3 A minimum of 100 mV of cathodic polarization. The formation or decay of polarization can be used to satisfy this criterion.

5.3 Alternative Reference Electrodes

5.3.1 Other standard reference electrodes may be substituted for the CSEs. However, their voltage measurements must be converted to the CSE equivalents as in Table 1:

Table 1: Conversion of Voltage Measurements to CSE Equivalents

	Equivalent to -0.85 V CSE	Correction
Calomel	-0.776 V	Add -0.074 V
Silver/Silver Chloride	-0.78 V	Add -0.07 V
Zinc	+0.25 V	Add -1.10 V

5.4 Special Considerations

5.4.1 Special cases, such as those involving stray currents and stray electrical gradients, that require the use of criteria different from those listed above, may exist. Measurements for current loss and gain on the structure and current tracing in the electrolyte have been useful in such cases.

5.4.2 Abnormal conditions in which protection is ineffective or only partially effective sometimes exist. Such conditions may include elevated temperatures, disbonded coatings, shielding, bacterial attack, and unusual contaminants in the electrolyte.

5.4.3 When structures that have dissimilar metals are protected, a negative structure-to-soil potential voltage equal to that for protection of the most anodic metal should be maintained.

Section 6: Cathodic Protection Design

6.1 General

6.1.1 Information regarding the design of impressed current and galvanic anode systems can be found in NACE Standard RP0169¹⁵ and in this standard. Information useful in the design includes:

- (a) site plan and system layout;
- (b) pipe, fittings, and other appurtenances;
- (c) pumps and power supplies;
- (d) existing and proposed CP systems;
- (e) nearby buried metallic structures;
- (f) site accessibility;
- (g) soil conditions (e.g., resistivity, chemical composition, aeration, and moisture);
- (h) electrical isolation;
- (i) coating integrity;
- (j) elevated temperatures;
- (k) shielding;
- (l) treated tank backfill material;
- (m) dissimilar metals and concrete/metal interfaces; and
- (n) complexing agents.

6.2 Galvanic Systems

6.2.1 This subsection describes the factors that should be considered in the design of external corrosion protection for existing UST systems using galvanic anode CP.

6.2.2 Galvanic protection systems can be applied to tank systems when the metallic surface area exposed to the soil is minimized through the application of a dielectric coating or when the surface area is small due to tank size. When current requirements are high, the use of impressed current CP should be considered to minimize the cost of the protection system (see Paragraph 6.3).

6.2.3 Electrical Isolation

6.2.3.1 Electrical isolation methods can be used to isolate the primary UST from other electrically grounded systems.

6.2.3.2 All uncoated associated piping can be electrically isolated from the tank. Submersible pumps can be isolated from the metallic piping

and tank by the use of dielectric isolating unions and bushings.

6.2.3.3 Electrical isolation of the piping can be accomplished by the use of flange isolation kits, dielectric bushings, or dielectric unions rated for the proper operating pressure and compatible with the product being stored in the tank. Use of dielectric unions underground should be avoided if at all possible. Dielectric unions should remain exposed for future inspection and maintenance.

6.2.3.4 When required by local codes and regulations, the tank shall be grounded to protect against damage due to lightning. This must be accomplished without compromising the CP design.

6.2.4 Galvanic Anode Selection

6.2.4.1 The three most common types of galvanic anodes that are effective in soil environments are standard-potential magnesium (ASTM B 843,¹⁶ **UNS⁽⁵⁾ M11632**), high-potential magnesium (ASTM B 843, **UNS M15102**), and high-purity zinc (ASTM B 418,¹⁷ **UNS Z13000**). The selection and use of these anodes are based on the current requirements for the structure to be protected, the soil conditions, and the temperature of the structure to be protected.

6.2.4.2 The current output from each type of anode depends greatly on the soil conditions, the anode shape, and the net driving potential of the anode.

6.2.4.3 When high-purity zinc anodes are employed, care shall be exercised to ensure the anodes meet the requirements of ASTM B 418, Type II anode material.¹⁸ The purity of the zinc greatly affects its performance as a galvanic anode for soil applications.

6.2.4.4 Zinc anodes shall not be used when the temperature of the anode environment is above 49°C (120°F). The high temperature can cause the anode to assume passive characteristics. The presence of some chemicals in the soil, such as carbonates, bicarbonates, and nitrates, may also affect the performance of bare zinc as an anode material.

6.2.4.5 Galvanic anode performance is enhanced with special backfill material. A mixture of 75% gypsum, 20% bentonite, and 5% sodium sulfate is

typically used with magnesium anodes. Either 75% gypsum, 20% bentonite, and 5% sodium sulfate or a mixture of 50% gypsum and 50% bentonite can be used with zinc anodes.

6.2.4.6 The anodes should be supplied with adequate lead wire attached. Lead wire shall be at least 4 mm² (#12 AWG⁽⁶⁾) solid wire with TW (thermoplastic insulated wire) or equivalent oil- and water-resistant insulation.

6.2.5 Galvanic Anode Installation

6.2.5.1 The CP anodes shall be installed around the tank in a manner that allows optimal current distribution. Anodes should be placed close to or below the elevation of the bottom of the UST. If multiple UST installations are spaced closely together, installation of additional anodes between the tanks and above the center line of the tanks may be required to provide adequate current distribution to the upper surfaces of the UST.

6.2.5.2 The anode lead wires shall be installed with sufficient slack to avoid possible damage due to settlement of surrounding soil.

6.3 Impressed Current Systems

6.3.1 This subsection recommends procedures for designing impressed current CP systems. In the design of a CP system, the following factors shall be considered:

- (a) recognition of hazardous conditions prevailing at the site and selection and specification of materials and installation practices that will ensure safe installation and operation;
- (b) all applicable regulatory codes;
- (c) selection and specification of materials and installation practices that will ensure dependable, economical operation of the system throughout its intended operating life; and
- (d) selection of proposed installation to minimize stray currents.

6.3.2 Electrical Continuity

6.3.2.1 All structures to be protected must be electrically continuous. Bonds may be required between piping and tanks and, in some cases, from tank to tank. Electrical conduits, hydraulic lifts, and utility piping, such as water and gas piping, must be investigated for isolation or continuity as required.

⁽⁵⁾ Metals and Alloys in the Unified Numbering System (latest revision), a joint publication of the American Society for Testing and Materials (ASTM) and the American Society of Automotive Engineers Inc. (SAE), Warrendale, PA.

⁽⁶⁾ American Wire Gauge (AWG): A particular series of specified diameters and thicknesses established as a standard in the United States and used for nonferrous sheets, rods, and wires. Also known as the Brown and Sharpe Gauge.

6.3.2.2 Nonwelded joints may not be electrically continuous. Electrical continuity between all components of the protected system must be verified.

6.3.3 Anode Systems

6.3.2.3 CP systems shall be designed to mitigate any adverse effects from stray current on foreign metallic structures within the influence of the CP system.

6.3.3.1 A variety of materials such as (a) high-silicon cast iron, (b) graphite, (c) mixed-metal-oxide-coated titanium, and (d) platinum-coated titanium or niobium are used for impressed current anodes. These anodes are normally installed with low-resistivity carbonaceous backfill.

6.3.3.2 Anode lead wires shall be constructed with insulation that meets the mechanical and chemical resistance requirements of the environment. Impressed current anodes shall be connected either singularly or in groups to the positive terminal of a DC source. The protected system components shall be connected to the negative terminal with insulated cable.

6.3.3.3 Cables between anodes, rectifiers, and negative returns from the structures to the rectifier require special insulation. It is good practice to install cables in plastic conduit. If installed in soil, the following cable insulation qualities are required:

- (a) abrasion resistance;
- (b) low moisture absorption; and
- (c) resistance to tank product spills.

6.3.3.4 The life of impressed current anodes can be extended by the use of low-resistivity, carbonaceous, conductive backfill around the anodes. The most common of these backfill materials are metallurgical coke breeze made from coal, and calcined petroleum coke. Low-resistivity, carbonaceous, conductive backfill also reduces the anode-to-earth resistance.

6.3.3.5 Anode groundbed configurations may be vertical, horizontal, or angle drilled. The selection of anode configuration is dependent on environmental factors, current requirements, current distribution, and the size and type of structure to be protected. Caution should be exercised to ensure that anode placement results in uniform distribution of protection current to the protected system surfaces.

6.3.3.6 The current requirement for achieving a given protection criterion can be determined by preliminary testing on existing structures through the use of temporary or simulated CP systems.

The current requirement can be estimated by calculating surface areas and applying a minimum protective current density based on experience and sound engineering judgment.

6.3.3.7 Although there are many sources of DC for impressed current CP, rectifiers are most commonly used. Various types of rectifiers such as (a) fixed voltage; (b) constant current; (c) automatic potential control; and (d) combinations of the above are available.

Separate terminal boxes with the DC power supply that can accommodate multiple circuit outputs that can be varied to individual circuits or anodes are available. These come equipped with shunts so that individual anode current outputs can be monitored.

6.3.3.8 All impressed current systems shall be designed with safety consideration as a priority. Caution should be exercised to ensure that all cabling is protected from physical damage and from the possibility of arcing. When required, rectifiers and junction boxes shall be explosion-proof.

6.4 Test Stations

6.4.1 Test stations for potential and current measurements should be considered for each system at sufficient locations to facilitate CP testing.

6.4.2 Test stations have a number of different configurations, including the following:

6.4.2.1 The test station can be cast iron or impact-resistant plastic but shall be set at grade in a manner to ensure its long-term durability. The test station may contain a terminal block. Wires should be color coded or otherwise permanently identified. Wire shall be installed with slack. Damage to insulation shall be avoided, and proper repairs must be made if damage occurs.

6.4.2.2 A test station can consist of a test lead continuous with the structure surface, secured by a nonconductive strap to a fixture, and accessible in the manhole opening.

6.4.2.3 If a portable reference electrode is used for monitoring, then an area of clean, unshielded backfill or soil should be made accessible in the manhole area for electrode placement.

6.4.3 Provisions should be made to monitor potentials at the bottom of tanks. Such facilities can include:

- (a) permanent reference electrodes, and
- (b) portable reference electrodes inserted in access tubes.

6.4.4 For galvanic anode CP systems, the test station design shall permit disconnection of the anodes to correct potential measurements for IR drop to evaluate the protection level. When desired, the test station should also accommodate test leads from buried reference electrodes.

6.4.5 The test station should be clearly marked, accessible, and installed so that it is protected from vehicular traffic.

6.4.6 All lead wires to the test station shall be protected from damage by either a minimum 0.5-m (18-in.) burial depth or a nonmetallic conduit.

6.5 Wire and Connections

6.5.1 Wire used for anode, reference electrode, and monitoring connections requires insulation with the following qualities:

- (a) low moisture absorption;
- (b) resistance to tank product spills;
- (c) abrasion resistance; and
- (d) sufficient breaking strength for the application.

6.5.2 Anode lead wires shall have the wire/anode interface connection secured by soldering or brazing.

Weld-on anodes shall have a weldable steel core for connection directly to the structure. Wiring attached to the structure should be connected by exothermic weld, weldable steel pressure wire connectors, or appropriate mechanical connectors, and should be able to withstand an acceptable pull test. The area of the connection shall be cleaned by scraping or brushing prior to attachment. The connector and connection area shall be thoroughly coated after attachment.

6.6 Miscellaneous

6.6.1 Design Drawings and Specifications

6.6.1.1 Drawings shall be prepared to show the overall layout of the structures to be protected, the CP system, and associated appurtenances.

6.6.1.2 Specifications shall be prepared for all materials and installation practices that are used in construction of the CP system.

6.6.2 Spill protection, overfill protection, release detection, vapor recovery measures, and electrical grounding or internal linings should be considered in the design of the CP system for the UST system.

Section 7: Installation of Cathodic Protection Systems

7.1 General

7.1.1 All work shall be performed in accordance with all applicable health and safety regulations.

7.1.2 Notifications

7.1.2.1 Coordinating Committees in the area (such as Underground Corrosion Control Coordinating Committees [UCCCs]⁽⁷⁾) and utility operators should be notified prior to construction and installation of the CP system(s).

7.1.2.2 Prior to excavation, public or private utility owners, as well as owners of other underground structures in the immediate vicinity, shall be notified. This provides the owners of underground structures with time to locate any structures within the proposed construction zone to avoid accidental physical damage.

7.2 Site Conditions

7.2.1 Pertinent as-built construction drawings from the UST installation shall be reviewed prior to construction. Although the location of most USTs can be determined, the location of product piping, vapor recovery lines, and vent lines can be difficult to determine. The underground structures at the facility include not only the USTs and associated piping, but also the monitoring wells and sensors, tank pit liners, and utilities that may be present.

7.2.2 Prior to installation of the CP system, certain factors such as water table, vehicular and pedestrian traffic, and aboveground structures shall be considered.

7.3 Installation Procedures

7.3.1 Although most installations do not normally disrupt operations, installation shall be coordinated with appropriate operations personnel to minimize any disruption of services. This work should also be coordinated with any other construction at the facility.

⁽⁷⁾ The NACE International Technical Activities Division may be contacted to determine whether a UCCC is registered in the area; Call +1 281/228-6200, or e-mail tcc@mail.nace.org.

7.3.2 All construction work performed on CP systems shall be done in accordance with construction drawings and specifications. All deviations from construction specifications shall be approved prior to installation and shall be noted on as-built drawings.

7.3.3 The installation of CP systems shall be under the supervision of trained and qualified personnel to ensure that the installation is done in accordance with the drawings and specifications.

7.3.4 Galvanic Anodes

7.3.4.1 Packaged anodes should be kept dry during storage. Electrical continuity between anode and lead wire shall be tested without compromising the integrity of the package. Any waterproof covering must be removed before installation.

7.3.4.2 Anodes shall be installed according to the system specifications. Packaged galvanic anodes shall be surrounded with select fill and compacted. Paragraph 6.2.4.5 describes the select fill. Also see Paragraph 3.6.1.

7.3.4.3 Care should be exercised so that lead wires and connections are not damaged during backfill operations. Lead wires should have enough slack to prevent strain. Anodes should not be carried or lowered into the excavation by the lead wire.

7.3.5 Impressed Current Anodes

7.3.5.1 Impressed current anodes shall be inspected for defects and for conformance to specified material. Care shall be exercised to avoid damaging the anodes during handling and installation.

7.3.5.2 Impressed current anodes shall be buried as indicated in construction specifications. Backfill material shall be placed to ensure that there are no voids around anodes. Backfilling operations shall not damage the anode or its lead wire.

7.3.5.3 Anode lead wires shall be carefully inspected for insulation defects. Extreme care shall be taken to avoid damaging the wire insulation. Anodes with damaged lead wire insulation shall not be installed.

7.3.6 Wire and Cable

7.3.6.1 Care shall be exercised when installing direct burial cable to the anodes to avoid damage to insulation. Sufficient slack shall be left to avoid strain. Backfill material around the cable shall be free of rocks and foreign matter that might damage the wire insulation when the wire is installed in a trench.

7.3.6.2 Underground splices of header cable to the groundbed should be avoided. Connections between header cable and conductors from anodes shall be mechanically secure and electrically conductive. If buried or submerged, all splices and connections must be sealed to prevent moisture penetration so that electrical isolation from the environment is ensured.

7.3.7 Rectifier Units

7.3.7.1 The rectifier unit shall be inspected to ensure that internal connections are mechanically secure and that no damage is present. Rating of the DC power source shall comply with construction specifications.

7.3.7.2 Cable connections to the rectifier shall be mechanically secure and electrically conductive. Before the power source is energized, it shall be verified that the negative cable is connected to the structure to be protected and that the positive cable is connected to the anodes. After the DC power source has been energized, measurements shall be made to verify that these connections are correct.

7.3.7.3 Alternating current (AC) wiring to rectifiers shall comply with local and national electrical codes and requirements of the utility supplying power. A disconnect switch external to the rectifier should be provided on a dedicated AC circuit. The rectifier case shall be properly grounded.

7.3.8 Wire Connections

7.3.8.1 The structure and all wires shall be clean, dry, and free of foreign materials when the connections are made. Connections of wires to the structure shall be installed so that they will remain secure and electrically conductive.

7.3.8.2 All wire attachments should be coated with an electrical isolating material. If the structure is coated, the isolating material shall be compatible with the coating and wire insulation.

7.3.8.3 Wire shall be installed with slack. Damage to insulation shall be avoided.

7.3.9 Isolating Devices

7.3.9.1 Inspection and electrical measurements shall be made to ensure that electrical isolation devices are effective.

7.4 System Commissioning

7.4.1 The energizing of CP systems for storage tanks shall be based on the initial design parameters. Major items that should be known are:

- (a) design criteria;
- (b) locations of CP equipment;
- (c) types of test facilities;
- (d) types of CP installed; and
- (e) proximity of foreign structures.

7.4.2 Prior to energizing any impressed current CP system, notification shall be given to operators of nearby utilities and pipelines.

7.4.3 Prior to energizing the CP systems, data and information shall be collected to provide an initial base line of items such as:

- (a) tank-to-soil potentials;
- (b) pipe-to-soil potentials;
- (c) dielectric isolation, if present;
- (d) foreign structure-to-soil potentials;
- (e) test coupons, if present; and
- (f) permanent reference electrodes, if present.

7.4.4 Verification of the following details regarding CP devices and hardware shall be made prior to energizing the system:

- (a) location of anodes;
- (b) ratings of impressed current sources;
- (c) location of test facilities; and
- (d) location of CP system negatives.

7.4.5 All initial base line data shall be documented and the records maintained for the life of the system. Any deviations from the design or as-built documentation shall be noted and included with the initial base line data.

7.4.6 Current Adjustment

7.4.6.1 The exact operating level of CP systems is determined by a series of tests at various operating levels. The specific operating level depends on the criterion for CP used for the UST system (see Section 5).

7.4.6.2 When adjusting the operating levels of CP systems, it is necessary to consider stray current effects on adjacent structures such as:

- (a) piping separated from the tank(s) or high-resistance fittings (e.g., threaded joints);
- (b) buried electric facilities;
- (c) buried fire protection piping;

- (d) buried water piping;
- (e) other adjacent tank systems; and
- (f) municipal or utility structures serving the facility at which the tank(s) is (are) located.

7.4.7 Testing

7.4.7.1 The final operating levels of CP systems shall be established to achieve the appropriate CP criterion (see Section 5).

7.4.7.2 Documentation of all operating parameters, such as initial base line data, as-built drawings, operating currents, locations of test facilities, key monitoring locations, equipment manuals, and ground water level, shall be done after the system is energized.

7.4.7.3 All appropriate electrical parameters shall be recorded and documented for future reference.

7.5 Records

7.5.1 Tank system information shall include the following:

- (a) dimension and capacity;
- (b) layout of pipe system;
- (c) date of installation;
- (d) type of excavation and installation details;
- (e) history of tank system performance and repairs;
- (f) history of previous corrosion system and performance; and
- (g) stored product.

7.5.2 Complete information about the design and installation of CP systems shall include:

- (a) power source capacity;
- (b) number and location of anodes;
- (c) anode material and design life;
- (d) anode installation details;
- (e) type, quantity, and location of permanent reference electrodes;
- (f) date of energizing and initial current and voltage;
- (g) structure-to-soil potential measurements;
- (h) results of continuity testing for all components listed in Paragraph 6.3.2;
- (i) approved as-built drawings for final CP system design; and
- (j) approved final commission report.

Section 8: Operation and Maintenance

8.1 General: This section recommends procedures and practices for maintaining continuous, effective, and efficient operation of CP systems on USTs.

8.1.1 Electrical measurements and inspection are necessary to determine that protection has been established according to applicable criteria and that each part of the CP system is operating properly.

8.1.2 Conditions that affect protection are subject to change with time. Corresponding changes may be required in the CP system to maintain protection.

8.1.3 Periodic measurements and inspections are necessary to detect changes in the CP system. Conditions in which operating experience indicates testing and inspections should be conducted more frequently than recommended in this standard may exist.

8.1.4 Care shall be exercised in selecting the location, number, and type of electrical measurements used to determine the adequacy of CP.

8.2 Maintenance Surveys

8.2.1 A survey shall be conducted after each CP system is energized to determine whether it satisfies applicable criteria (see Section 5) and operates efficiently (see Paragraph 7.4).

8.2.2 Monitoring

8.2.2.1 All corrosion control systems shall be monitored in accordance with NACE Standard TM0101¹⁸ to assure effective operation as designed. The system shall be tested to verify its effectiveness after installation and whenever construction or maintenance in the area of the structure occurs.

8.2.2.2 Field-installed galvanic and impressed current CP systems shall be tested annually.

8.2.2.3 A factory-installed CP system shall be tested at an interval not to exceed three years if manufactured in accordance with a nationally recognized standard or code.

8.2.3 Inspection, surveys, and tests of CP systems shall be made to ensure their effectiveness and proper operation and maintenance as follows:

8.2.3.1 All sources of impressed current shall be checked at intervals not exceeding two months. Evidence of proper functioning may be current output, normal power consumption, or a signal indicating normal operation.

8.2.3.2 All impressed current CP facilities shall be inspected annually as part of a preventive maintenance program to minimize in-service failure. Inspections should include a check for electrical shorts, ground connections, meter accuracy, efficiency, and circuit resistance. The effectiveness of isolating devices and continuity bonds should be evaluated during the periodic surveys. This can be accomplished by on-site inspection or by evaluating corrosion test data.

8.2.4 Test equipment used for obtaining each electrical value shall be of an appropriate type (See Paragraph 4.4.4). Instruments and related equipment shall be maintained in good operating condition and checked annually for accuracy.

8.3 Visual Inspection: If the UST or any part of the system is uncovered, visual inspection for evidence of corrosion and coating deterioration should be made. The necessary repairs should be implemented to ensure continued corrosion protection of the UST.

8.4 Remedial measures shall be taken when periodic tests and inspections indicate that protection is no longer adequate according to applicable criteria (see Section 5). These measures may include the following:

8.4.1 Repair, replacement, or adjustment of CP system components.

8.4.2 Providing supplementary facilities when additional protection is necessary.

8.4.3 Repair, replacement, or adjustment of continuity and interference bonds.

8.4.4 Elimination of accidental metallic contact.

8.4.5 Repair of defective isolating devices.

8.5 Records

8.5.1 All records of the CP system including the following shall be maintained by the owner for the life of the system.

8.5.2 A record of surveys, inspections, and tests shall be maintained to demonstrate that applicable criteria for CP have been satisfied (see Section 5).

8.5.3 Relative to the maintenance of corrosion control facilities, the following information shall be recorded:

8.5.3.1 Maintenance of CP facilities.

8.5.3.1.1 Repair of rectifiers and other DC power sources.

8.5.3.1.2 Repair or replacement of anodes, connections, and cable.

8.5.3.2 Maintenance, repair, and replacement of coating, isolating devices, test leads, and other test facilities.

8.5.4 Records sufficient to demonstrate the evaluation of the need for and the effectiveness of corrosion control measures should be retained as long as the facility involved remains in service. Other related corrosion control records should be retained for a period that satisfies individual company needs.

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16. ASTM B 843 (latest revision), "Standard Specification for Magnesium Alloy Anodes for Cathodic Protection" (West Conshohocken, PA: ASTM).
17. ASTM B 418 (latest revision), "Standard Specification for Cast and Wrought Galvanic Zinc Anodes" (West Conshohocken, PA: ASTM).
18. NACE Standard TM0101 (latest revision), "Measurement Techniques Related to Criteria for Cathodic Protection on Underground or Submerged Metallic Tank Systems" (Houston, TX: NACE).

Standard Recommended Practice

Corrosion Control of Steel Fixed Offshore Structures Associated with Petroleum Production

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Revised 2003-06-21
Revised March 1994
Revised May 1983
Approved April 1976
NACE International
1440 South Creek Drive
Houston, Texas 77084-4906
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ISBN 1-57590-170-6
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Foreword

Offshore structures represent large capital investments. Structures are being placed in offshore areas worldwide and are being designed to withstand forces resulting from hurricanes, arctic storms, tidal currents, earthquakes, and ice floes. Moreover, platform structures are currently being placed in deeper waters and, therefore, have become larger, more complex, and more expensive. Control of corrosion on structures is necessary for the economic development of oil and gas production, to provide safe support for working and living areas, and to avoid potential harm to the environment. For the purposes of this standard, offshore structures are considered to be stationary structures (platforms or subsea facilities) that are fixed to the sea floor by gravity, piling, and/or mooring cables.

This NACE International standard is intended for use by corrosion control personnel concerned with the corrosion of steel fixed offshore platforms associated with petroleum production. It outlines materials, practices, and methods for control of corrosion for steel fixed structures associated with petroleum production located in offshore areas. The purpose is to facilitate more effective corrosion protection of structures by the presentation of reliable information. Corrosion on offshore structures can be divided into three major areas: the submerged zone, the splash zone, and the atmospheric zone. The submerged zone also includes that portion of the structure below the mudline. This standard does not include procedures for the control of internal corrosion of wells, piping, and associated equipment that may be in use on the structure, but does include external protection of these items in the atmospheric zone on the structure.

This standard was originally issued in 1976 and revised in 1983 by Task Group (TG) T-1-2 on North Sea Corrosion Problems. It was revised in 1994 by Task Group T-1-5 and in 2003 by Task Group 170, which is administered by Specific Technology Group (STG) 30 on Oil and Gas Production—Cathodic Protection. TG 170 is sponsored by STGs 02 on Protective Coatings and Linings—Atmospheric and STG 05 on Cathodic/Anodic Protection. It is issued by NACE International under the auspices of STG 30.

<p>In NACE standards, the terms <i>shall</i>, <i>must</i>, <i>should</i>, and <i>may</i> are used in accordance with the definitions of these terms in the <i>NACE Publications Style Manual</i>, 4th ed., Paragraph 7.4.1.9. <i>Shall</i> and <i>must</i> are used to state mandatory requirements. The term <i>should</i> is used to state something good and is recommended but is not mandatory. The term <i>may</i> is used to state something considered optional.</p>
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NACE International Standard Recommended Practice

Corrosion Control of Steel Fixed Offshore Structures Associated with Petroleum Production

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Section 1: General

1.1 This standard provides guidelines for establishing minimum requirements for the control of corrosion on steel fixed offshore structures associated with petroleum production, and on the external portions of associated oil and gas handling equipment. Fixed structures include platforms, tension leg platforms (TLPs), and subsea templates. This standard does not include guidelines for corrosion control of temporarily moored mobile vessels used in petroleum production.

1.2 For this standard, corrosion on structures is divided into three zones: the submerged, splash, and atmospheric zones. Each zone is examined separately.

1.3 This standard does not designate guidelines for every specific situation because of the complexity of environmental conditions. In many instances, there may be several solutions to the problem and, when appropriate, meritorious alternative solutions have been included.

1.4 This standard does not include guidelines for corrosion control of the internal portions of wells, piping, and associated equipment that may be installed on or attached to structures.

1.5 This standard includes corrosion control of the external surfaces of attached pipelines above the splash zone. When ownership of the pipeline is different from that of the structure, the structure owner's responsibility for the pipeline usually ends at a designated point or valve on the structure.

1.6 Underwater pipelines and pipeline risers are specifically excluded from this standard.

1.7 Alternative methods are acceptable to accomplish the objectives of this standard; however, deviation should be made only if, in the opinion of a competent corrosion specialist, the objectives expressed in the standard have been achieved.

Section 2: Definitions

NOTE: Additional definitions for cathodic protection and coatings technology may be found in NACE Standard RP0169,¹ the *NACE Corrosion Engineer's Handbook*,² and the NACE International 2002 *Glossary of Corrosion-Related Terms*.³

Anchor Pattern: The irregular peak and valley pattern created on the surface of steel by the effect of blasting media hitting the steel at high velocity.

Anode: The electrode of an electrochemical cell at which oxidation occurs. Electrons flow away from the anode in the external circuit. Corrosion usually occurs and metal ions enter the solution at the anode.

Atmospheric Zone: The zone of the structure that extends upward from the splash zone and is exposed to sun, wind, spray, and rain.

Calcareous Coating or Deposit: A layer consisting of calcium carbonate and other salts deposited on the surface. When the surface is cathodically polarized as in cathodic protection, this layer is the result of the increased pH adjacent to the protected surface.

Cathode: The electrode of an electrochemical cell at which reduction is the principal reaction. Electrons flow toward the cathode in the external circuit.

Cathodic Disbondment: The destruction of adhesion between a coating and the coated surface caused by products of a cathodic reaction.

Cathodic Protection: A technique to reduce the corrosion of a metal surface by making that surface the cathode of an electrochemical cell.

Chalking: The development of loose, removable powder (pigment) at the surface of an organic coating, usually caused by weathering. Controlled chalking provides for self-cleaning of the surface and leaves the surface in good condition for recoating.

Chlorinated Rubber: A particular film former used as a binder, made by chlorinating rubber.

Corrosion: The deterioration of a material, usually a metal, that results from a reaction with its environment.

Corrosion Specialist: A person who, by reason of his/her education and/or experience, is qualified to evaluate and solve problems related to the corrosion of materials. In this standard, corrosion specialist refers to one who is qualified in the control of corrosion in marine environments.

Crosslink: The result of a chemical reaction linking two chains in the molecular structure of a coating and changing the final state of the coating.

Current: (1) A flow of electric charge. (2) The amount of electric charge flowing past a specified circuit point per unit time, measured in the direction of net transport of positive charges. (In a metallic conductor, this is the opposite direction of the electron flow.)

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Current Density: The current to or from a unit area of an electrode surface.

Depolarization: The removal of factors resisting the current in an electrochemical cell.

Dielectric Shield: An electrically nonconductive material, such as a coating, sheet, or pipe, that is placed between an anode and an adjacent cathode, usually on the cathode, to improve current distribution in a cathodic protection system.

Doubler Plate: An additional plate or thickness of steel used to provide extra strength at the point of anode attachment to a structure.

Electrical Isolation: The condition of being electrically separated from other metallic structures or the environment.

Electrolyte: A chemical substance containing ions that migrate in an electric field.

Epoxy: Type of resin formed by the reaction of aliphatic or aromatic polyols (like bisphenol) with epichlorohydrin and characterized by the presence of reactive oxirane end groups.

Faying: Especially close fitting. The term originally described the fit between hull timbers in wooden ships.

Foreign Structure: Any metallic structure that is not intended as a part of a system under cathodic protection.

Galvanic Anode: A metal that provides sacrificial protection to another metal that is more noble when electrically coupled in an electrolyte. This type of anode is the electron source in one type of cathodic protection.

Holiday: A discontinuity in a protective coating that exposes unprotected surface to the environment.

Impressed Current: An electric current supplied by a device employing a power source that is external to the electrode system. (An example is direct current for cathodic protection.)

Interference Current (Stray Current): Current through paths other than the intended circuit. For the purposes of this standard, interference current is current discharged to the electrolyte from a structure that may be either (1) not an intended part of the circuit or (2) an intended part of the circuit that is not adequately connected to the current source.

Inorganic Zinc-Rich Coating (Paint): Coating containing a metallic zinc pigment (typically 75 wt% zinc or more in the dry film) in an inorganic vehicle.

“J” Tube: A curved tubular conduit designed and installed on a structure to support and guide one or more pipeline risers or cables.

Mill Scale: The oxide layer formed during hot fabrication or heat treatment of metals.

Mudline: The ocean floor at the location of interest.

Padeye: A lifting or connection point that is shaped like an eye and is used to accommodate hooks, tackle, or slings.

Pipeline: A conduit for carrying produced oil, water, and gas between structures or between structures and onshore processing facilities.

Platform: An offshore structure used to accommodate oil and/or gas wells, related production equipment, pipelines, and/or living quarters.

Polarization: The change from the open-circuit potential as a result of current across the electrode/electrolyte interface.

Polymerization: The process of uniting a number of small chemical units to form a larger one. The product of such a union is called a *polymer*.

Primer: A coating material intended to be applied as the first coat on an uncoated surface. The coating is specifically formulated to adhere to and protect the surface as well as to produce a suitable surface for subsequent coats. (Also referred to as *Prime Coat*.)

Reference Electrode: An electrode whose open-circuit potential is constant under similar conditions of measurement, which is used for measuring the relative potentials of other electrodes.

Resin: Generally refers to a class within the broad family of plastics or polymers and usually indicates stability for use as a binder for coating materials. The term resin is usually modified by other words to denote type, for example: alkyd resin, vinyl resin, ester resin, or epoxy resin.

Riser: (1) That section of pipeline extending from the ocean floor up to an offshore structure. (2) The vertical tube in a steam generator convection bank that circulates water and steam upward.

Silver/Silver Chloride Electrode: For the purposes of this standard, a reference electrode that uses seawater as the junction electrolyte, for example, the Ag/AgCl/seawater electrode.

Splash Zone: The zone of the structure that is alternately in and out of the water because of the influence of tides, winds, and seas. Excluded from this zone are surfaces that are wetted only during major storms.

Structure: Stationary structure (platform or subsea facility) that is fixed to the sea floor by gravity, piling, and/or mooring cables.

Structure-to-Electrolyte Potential: The potential difference between the surface of a buried or submerged metallic structure and the electrolyte that is measured with reference to an electrode in contact with the electrolyte.

Submerged Zone: The zone that extends downward from the splash zone and includes that portion of the structure below the mudline.

Subsea Template: A structure intended to be placed on the sea floor to accommodate oil and/or gas wells, related production equipment, and/or pipelines.

Thinner: A volatile solvent used to lower the viscosity of a coating material.

Thermoplastic: A material capable of being repeatedly softened by heat and hardened by cooling.

Thermosetting: A material that undergoes a chemical reaction from the action of heat and pressure, catalysts, and ultraviolet light, leading to a relatively infusible state.

Tie Coat: A special-purpose intermediate coat, usually organic, used to act as a bridge between a primer and finish coat to overcome either incompatibility or application problems between the primer and finish coats.

Urethane: A chemically cured coating consisting of a solution vinyl, vinyl acrylic, or acrylic base reacted with isocyanate converter to form a tough, durable, glossy coating.

Valve Reach Rod: A long valve stem extension that enables personnel on the surface to open and close a ballast control valve located near the bottom of the structure.

Vinyl Acrylic: Vinyl resin modified with acrylic resin in solvent solution.

Vinyl Coatings: Vinyl resin dissolved in a solvent. Vinyl solution coatings may be air dried or baked.

Voltage: An electromotive force, or a difference in electrode potentials, expressed in volts or millivolts.

Voltage Drop: The voltage across a current-carrying resistance in accordance with Ohm's Law.

Wash Primer: A thin, inhibiting primer, usually chromate pigmented, with a polyvinyl butyral binder.

Wear Plate: A sacrificial member attached to the structure in the splash zone to protect it from anticipated corrosion and/or erosion caused by ice and/or high-velocity, silt-laden water.

Section 3: Structural Design for Corrosion Control

3.1 Introduction

3.1.1 This section recommends design features that simplify corrosion control of structural steel in the atmospheric, splash, and submerged zones of offshore structures. The structural design parameters that must be considered for an offshore structure to resist dynamic and static loads are the responsibility of civil and structural engineers and are not a part of this standard.

3.2 Splash Zone

3.2.1 This is the zone of an offshore structure that is alternately in and out of the water because of the influence of tides, winds, and seas. Excluded from this zone are surfaces that are wetted only during major storms. In the Gulf of Mexico, the splash zone typically covers an interval of about 2 m (6 ft); in Cook Inlet, Alaska, the interval approaches 9 m (30 ft); during winter storms the splash zone in the North Sea can be 10 m (33 ft).

3.2.2 A structure should be designed to minimize the surface area of steel in the splash zone. Intersecting "T," "K," and "Y" joints should be avoided in the splash zone.

3.2.3 Methods for controlling corrosion in the splash zone are presented in Section 10.

3.2.4 Added metal thickness, either as a weld-applied wrap or as a heavier-wall tubular member, may be used to compensate for anticipated splash zone corrosion over the life of an offshore structure.

In determining the required level of added wall thickness the following factors should be taken into account:

- Required life of the structure
- Use of lifetime minimum or no maintenance coatings (e.g., thermal-sprayed aluminum)
- Maintenance philosophy if there is coating damage (how long is it likely to be left to corrode before the coating is repaired)
- Corrosion rate of carbon steel in seawater at the location the structure will be installed

3.2.5 Piping, etc., passing through the splash zone, that is to be removed after installation, should preferably be clamped to the structural member, not welded to it.

3.3 Atmospheric Zone

3.3.1 This zone of an offshore structure extends upward from the splash zone. It is exposed to sun, wind, spray, and rain.

3.3.2 Corrosion in this zone is typically controlled by the application of a protective coating system (see Section 12). Steel surface areas requiring coating should be minimized and/or made accessible by:

3.3.2.1 Substituting tubular members for other structural shapes.

3.3.2.2 Seal welding and “boxing in” structural units.

3.3.2.3 Eliminating skip welding.

3.3.2.4 Eliminating close-fitting and faying surfaces.

3.3.2.5 Providing padeyes to make scaffolding and maintenance painting easier.

3.3.3 Nonferrous and nonmetallic materials minimize atmospheric corrosion problems. For example, quarters modules and lifeboats are available in aluminum and composite materials such as glass-reinforced polyester (GRP). Corrosion-resistant materials and composites can be used for handrails, electrical conduit, stair treads, and deckplates. When dissimilar metals are used, care must be taken to prevent galvanic corrosion of the active component. Composite materials such as GRP may be substituted for metals when resistance to corrosion and/or weight reduction is desired. Safety aspects regarding the use of these materials should be considered.

3.3.4 Drilling fluids can damage protective coating systems and nonferrous metals such as aluminum and zinc. Solid decks, splash walls, and a good drainage system minimize coating damage and pollution caused by drilling fluids.

3.4 Submerged Zone—External Areas

3.4.1 This zone extends downward from the splash zone and includes any portion of the structure below the mudline. Corrosion control for the external areas of the submerged zone should be achieved through the application of cathodic protection (CP) or by CP in conjunction with coatings. To simplify the application of effective cathodic protection, the following design features are recommended:

3.4.1.1 Tubular members should be used wherever possible. Recessed corners in channels and “I” beams are difficult to protect. The crevice formed by placing angles or channels back-to-

back cannot be reliably protected, and such construction should not be used.

3.4.1.2 For structures in which fatigue or corrosion fatigue is a critical factor, welds may be stress relieved to reduce the likelihood of fatigue or corrosion fatigue failures in the heat-affected zone (HAZ). This may be important in cold-water environments, where polarization tends to develop slowly, or in partially shielded areas on a structure. See API⁽¹⁾ RP 2A-WSD⁴ and RP 2A-LRFD.⁵

3.4.1.3 All weld joints should be continuous. Skip and tack welding should not be used. If lap joints are used, both edges should be continuously welded. Bolted and riveted fittings should be avoided.

3.4.1.4 Ballast control valve reach rods should be designed so that they can be removed after a structure has been set, whenever practical. If left in place, they may shield adjacent structural members from the CP current. Loose reach rods can also cause chafing damage to the structure.

3.4.1.5 Piping, such as grout lines, well cutting lines, discharge lines, water supply casings, and pipeline risers, if clustered around a large structural member, can cause shielding and interfere with the flow of CP current. Piping not needed for continued operations should be removed if economically feasible. Lines not scheduled for removal should be located to avoid CP shielding. A minimum clear spacing of 1.5 diameters of the smaller pipe should be provided. Coatings may be used to minimize CP shielding.

3.4.1.6 Supplemental or replacement impressed current anodes are sometimes required after a structure has been placed in service. Designers should consider providing spare “J” tubes for pulling cables for add-on anodes and/or providing brackets, guides, or clamps to facilitate such anode additions or replacement.

3.4.1.7 Structure pilings should be protected by the structure CP system. Piles driven through jacket legs are normally bonded to the jacket by welding, and thus receive CP. Skirt piles are typically driven inside submerged piling grout tubes and then are grouted in place. Skirt piles may be electrically connected to the jacket by means of guide shoes, centralizers, or other acceptable bonding methods. Corrosion rates below the mudline are considered to be low. However, mudline corrosion can be significant for structures with long lifetimes. All mudline members, critical to the integrity of the offshore structure, should be properly connected to the CP system.

⁽¹⁾American Petroleum Institute (API), 1220 L St. NW, Washington, DC 20005.

3.4.1.8 Well-casing conductors must be electrically connected to the structure when the well-casing conductors are considered necessary to the integrity of the well casings.

3.4.1.9 All steel to be protected must have electrical continuity with the CP system (preferably by welded contact). This electrical continuity should be capable of lasting for the lifetime of the structure.

3.5 Submerged Zone—Internal Areas

3.5.1 Corrosion normally is negligible on the internal surfaces of structural members or in compartments that are sealed and have no contact with either the atmosphere or the seawater. Whenever possible, the design should provide for sealed compartments.

3.5.2 During offshore structure launching and tilt-up operations, some structural members are flooded and remain flooded for the life of the structure. To prevent internal corrosion, the flooding valves should be closed after flooding, to isolate the flooded chambers from contact with atmospheric oxygen. In compartments in which circulation of seawater is possible, provisions should be made to curtail internal corrosion. CP or a combination of CP and coatings should be used. Tanks and compartments with a gas phase should be coated internally where condensation may occur and CP is not effective. The use of impressed current systems in these compartments should be avoided due to development of toxic and corrosive chlorine gas by the anode.

3.5.2.1 Piping, valves, submerged pumps, and other special equipment must also be protected; particularly when different metallic materials are used there is high risk of galvanic corrosion. This is important, for example, when corrosion-resistant alloy piping is routed through structural steel bulkheads.

3.5.3 In flooded compartments with a source of organic nutrients, bacterial growth may generate organic acids, carbon dioxide, and/or hydrogen sulfide (H_2S) that can cause corrosion. Bacteria-related corrosion can be controlled by the use of internal CP, coatings, and/or microbiocides. **Caution:** H_2S is toxic, even at low concentrations.

3.5.4 Pipelines are sometimes installed in pull tubes, or “J” tubes. To restrict contact with seawater and atmospheric oxygen, the pull-tube annulus should be sealed at the above-water end with a suitable nonwick-

ing packing after the lines have been pulled into position.

3.5.5 Floating production units have mooring systems intended for long-term service. Special considerations are required for the corrosion protection of these mooring lines.

3.5.5.1 Chains: Chains are protected by corrosion allowance. Corrosion allowance is added on the diameter of the chain (bar), such that twice the corrosion rate at the location must be used when calculating the additional material. In the splash zone a higher corrosion allowance is required. Depending on chain handling, the wear could be substantial. Many permanent floating production units require minimal handling of the mooring systems. Instead of full corrosion allowance in the splash zone, the splash zone chain segment can be “turned” once during the lifetime; thus the submerged part becomes the splash zone part and vice versa after half the intended design life.

Experience has shown that CP on the structure is effective approximately 30 to 60 m (100 to 200 ft) out from the structure. The distance depends on the connection of the chain to the structure, the size of the chain, and the line tension. This CP should not be included in the mooring line design, but additional CP must be applied to prevent underprotection of the steel fairleads and steel structure.

3.5.5.2 Wire ropes: Wire ropes are normally made from galvanized wires and have an outer extruded corrosion protection jacket from polyurethane, polyethylene, or a similar material. In addition, grease is injected to prevent water from penetrating into the rope and ease movement between the individual wires. Sacrificial zinc wires may be included. Because steel wires have very high strength, hydrogen effects should be evaluated as part of any CP of the ropes.

It is important that the external jacket completely cover the connection of the wire rope to the socket end and prevent water from penetrating into the wire rope.

3.5.5.3 For mooring lines and anchors, bacterial corrosion in the parts exposed to bottom sediments must be evaluated and, if necessary, protection measures taken in the form of CP, coating, or corrosion allowance.

Section 4: Criteria for Cathodic Protection

4.1 Introduction

4.1.1 This section lists criteria and related inspection methods for CP. Compliance with the criteria either separately or collectively indicates whether the structure is protected.

4.2 General

4.2.1 The objective of using CP is to control the corrosion of metallic surfaces in contact with electrolytes.

4.2.2 The criteria in Paragraph 4.3 have been developed through laboratory experiment or field experience. Structure protection need not be limited to these criteria if it can be demonstrated by other means that control of corrosion has been achieved.

4.2.3 The selection of a particular criterion for achieving the objective in Paragraph 4.2.1 depends, in part, on past experience with similar structures and environments in which the criterion has been used successfully.

4.2.4 No single criterion for evaluating the effectiveness of CP has proved to be satisfactory for all conditions. A combination of criteria may be needed for a single structure.

4.3 Criteria

4.3.1 Potential measurements

4.3.1.1 A negative (cathodic) voltage of at least -0.80 V measured between the structure surface and a silver/silver chloride (20 ohm-cm seawater) reference electrode (Ag/AgCl [sw]) contacting the water is necessary. Normally, this voltage should be measured with the protective current applied. This -0.80 V criterion includes the voltage drop across the steel/water interface, but does not include the voltage drop in the water (see Paragraphs 4.5.1.1 and 4.6.1).

4.3.1.2 As an alternative to the criterion in Paragraph 4.3.1.1, a minimum negative (cathodic) voltage shift of 300 mV is produced by the application of protective current. This voltage shift shall be measured between the structure surface and a reference electrode contacting the water; it includes the voltage drop across the steel/water interface, but does not include the voltage drop in the water (see Paragraphs 4.5.1.1 and 4.6.1).

4.3.1.3 The potential at which corrosion is controlled is a function of the temperature and the environment. In waters exposed to the air and at typical ambient temperatures, the criteria listed in Paragraphs 4.3.1.1 and 4.3.1.2 have proved to be satisfactory. For other circumstances, the potential to control corrosion can be estimated using the Nernst equation.⁶

4.3.2 Visual inspection

4.3.2.1 Any visual inspection method (diver visual or feel, physical measurement, photography, or television) should indicate no progression of corrosion beyond limits acceptable for intended structure life throughout the structure.

4.3.3 Coupons

4.3.3.1 Corrosion type and rate must be within limits acceptable for intended structure life.

4.4 Alternative Reference Electrodes

4.4.1 Other standard reference electrodes that may be substituted for the Ag/AgCl (sw) are listed below with their voltage equivalent to -0.80 V referred to a Ag/AgCl (sw):

4.4.1.1 Saturated copper/copper sulfate reference electrode (CSE): -0.85 V (or more negative for protection). NOTE: This electrode is not stable for long-term immersion service.

4.4.1.2 High-purity zinc reference electrode: +0.25 V (or less positive for protection) corresponding to ASTM⁽²⁾ (B 418⁷ Type II, high-purity zinc having the following composition limits: aluminum: 0.005% maximum; cadmium: 0.003% maximum; iron: 0.0014% maximum; zinc: balance.

4.4.1.3 Saturated calomel reference electrode (SCE [saturated KCl]): -0.78 V (or more negative for protection).

4.4.1.4 MIL specification⁽³⁾ zinc reference electrode: +0.25 V (or less positive for protection) corresponding to MIL-A-18001⁸ having the following composition limits: aluminum: 0.10% to 0.50%; cadmium: 0.025% to 0.15%; iron: 0.005% maximum; lead: 0.005% maximum; copper: 0.005% maximum; silicon: 0.125% maximum.

⁽²⁾ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA 19428.

⁽³⁾Military Specification, available from Government Printing Office, Washington, DC 20402.

4.4.1.5 Ag/AgCl (saturated KCl): -0.76 V (or more negative for protection).

4.5 Methods of Measuring and Evaluating CP

4.5.1 The most common method of evaluating the CP level is to measure electrical potential between the structure and a suitable reference electrode.

4.5.1.1 Potential measurements should be made with the reference electrode located in the water as close as practicable to the structure to minimize included voltage drops. Measurements taken with the electrode close to a structure member but distant from anodes and in areas of greatest shielding should be given major consideration in evaluating the protective level of a structure.

4.5.1.2 The most frequently used method of measuring potentials involves suspending the reference electrode freely in the water from a designated location on the structure. The electrode is lowered to a specified series of depths for readings, and the process is repeated at other appropriate points on the structure. The location of the electrode may not be known because of drift resulting from water currents. This method is useful for determining the general condition of the CP system, but may not define problem areas on marginally protected structures.

4.5.1.3 The reference electrode may be carried by a diver or a remotely operated vehicle (ROV). This method provides excellent knowledge of electrode location and can result in a potential survey in any desired degree of detail. Diver safety must be considered during evaluation of impressed current protected structures. This may involve limiting the output from or de-energizing at least a part of the system for the duration of the measurements. If the system is de-energized, the effect of the reduction on the level of protection should be considered during the evaluation of the potential measurements.

4.5.1.4 The reference electrode may be run down a guide wire for better control of its location. The guide wire may be permanently installed on the structure, or it may be temporarily installed with the aid of a heavy weight to anchor it at the bottom. If temporarily installed, the wire (if metallic) should be electrically isolated from the structure. The guided electrode is capable of providing more accurate potential information than the freely suspended electrode, depending on the proximity of the guide wire to the members of the structure.

4.5.1.5 A number of permanent reference electrodes may be mounted on a structure. While the exact electrode locations are known, the information obtained from these electrodes is limited to the adjacent structure surfaces.

Although this limitation holds true for any potential measurement, this method can provide a reproducible basis for comparing potentials at different times. The accuracy of permanent electrodes should be periodically checked against another electrode. Dual reference electrodes that combine zinc and silver-silver chloride references into a single installed permanent unit also help to detect/reduce malfunctions.

4.5.1.6 In addition to reference electrodes, some structures have been equipped with permanent monitors to measure current density and current output from representative galvanic anodes. These devices are particularly useful when dealing with new structure designs, or new environments in which precise CP design criteria are not available. These devices typically use calibrated shunts to arrive at the current output or current density value; signals are usually transmitted topside using hard-wired connections.

4.5.2 In addition to potential surveys, current density surveys can produce valuable data. Current density surveys utilize specially designed reference electrode arrays that measure the voltage gradient in the seawater around the structure. Although these surveys do not determine the level of protection present on the structure, they may be useful in determining current distribution and predicting remaining anode life.

4.5.3 Visual inspection is sometimes used to gain detailed knowledge not attainable by other means.

4.5.3.1 Divers may be employed to inspect visually or by feel if turbidity or light conditions so dictate.

4.5.3.2 Visual inspection using suitable instruments may include physical measurements such as the crack length and depth, wall thickness, or pit depth, as well as anode size and condition.

4.5.3.3 Underwater photography may be used to provide a permanent record of conditions.

4.5.3.4 Underwater television can provide a running topside view if decisions must be made while underwater work is in progress. Videotapes can provide a permanent record of the underwater conditions.

4.5.4 Steel coupons with metallurgy similar to that of the structure can be placed on a structure for later removal to determine the effectiveness of corrosion control measures. Coupons might be especially useful in areas suspected of being comparatively inaccessible to CP current.

4.6 Precautionary Notes

4.6.1 Consideration should be given to voltage (IR) drops other than those across the steel/water interface when structure potential data are evaluated.

4.6.1.1 Changes in water resistivity from causes such as freshwater flow from a river or temperature variation affect the included voltage drop.

4.6.1.2 In impressed current systems, under conditions involving high-resistivity water and/or high current density, the voltage drop may be excessive. Potential measurements taken immediately after turning off the rectifier(s) may provide useful information by eliminating voltage drop in the water.

4.6.1.3 In conventionally designed galvanic anode protection systems, current-off readings are not possible. However, the included voltage drop is generally not significant in ordinary seawater if the reference electrode is placed close to the structure.

4.6.2 Storm waves or strong tides can produce high water velocities that tend to depolarize the structure. Higher water levels also add additional areas of unprotected steel and increase the current required to produce protective potentials. Depolarization is less likely to be a problem for well-polarized structures with well-formed calcareous deposits or for coated steel structures.

4.6.3 Marine growth may mask the true condition of the steel surface during a visual inspection; it must be removed from the areas being inspected. All potential measurements on the structure shall be made before removal of marine growth. The removal process could depolarize the steel and might result in erroneous measurements.

4.6.4 Coupons normally are small and care must be taken in extending coupon data to cover other areas or the entire structure on protected structures.

4.6.5 The Ag/AgCl (sw) potential is somewhat affected by the resistivity, e.g., the chloride content, of the seawater in which the electrode is immersed. If the resistivity is known to differ appreciably from that of ordinary

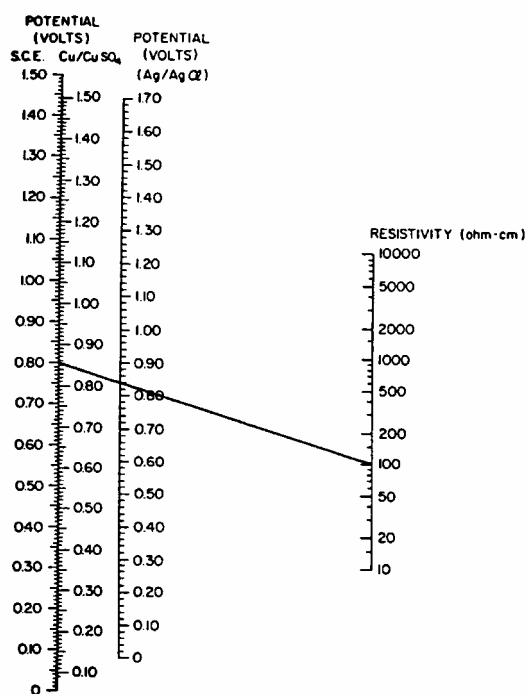


FIGURE 1

Nomogram for the correction of potential readings made with the Ag/AgCl electrode in waters of varying resistivity to the saturated calomel or Cu/CuSO₄ scale.^{(4),9}

⁽⁴⁾ Nomogram courtesy of M.H. Peterson, Naval Research Laboratory (NRL), Washington, DC and R.E. Groover, NRL Marine Corrosion Laboratory, Key West, FL.

seawater (20 ohm-cm), the electrode reading should be corrected in accordance with the nomogram shown in Figure 1. For example, if brackish water of 100 ohm-cm resistivity exists at the structure site, the minimum protective potential to Ag/AgCl electrode is -0.83 V, corresponding to -0.85 V to CSE.

4.6.6 At water depths progressively beyond 300 m (1,000 ft) and sometimes at shallower depths, seawater characteristics (dissolved oxygen, temperature, salinity, pH, sea currents, and fouling) may vary significantly from surface and shallow depths and affect cathodic polarization and calcareous deposit formation. A site-specific survey for CP performance and seasonal variation of seawater characteristics is helpful in the design of an effective CP system for deep water.

4.7 CP can affect the corrosion fatigue properties of the structure.

4.7.1 CP at typical potential values tends to restore the steel to the "in-air" fatigue value.

4.7.2 The rate of propagation of fatigue cracks may be accelerated in some steels with highly negative CP potentials. Fatigue crack growth data may be used to establish whether highly negative potentials are significant.

4.7.3 The calcareous coating may plug fatigue cracks, reducing crack growth.

4.7.4 Corrosion should be controlled in highly stressed locations to prevent pitting that might promote fatigue cracks.

Section 5: Design of Cathodic Protection Systems

5.1 Introduction

5.1.1 This section recommends procedures for designing CP systems that provide effective corrosion control for offshore structures.

5.1.2 In the design of an offshore CP system, environmental factors must be understood, and consideration should be given to the following:

5.1.2.1 Selection and specification of materials, equipment, and installation practices that ensure the safe installation and operation of the CP system.

5.1.2.2 Specification of materials and installation practices in conformance with applicable codes, regulations, and standards that may be issued by the following:

- (a) Structure operator,
- (b) NACE International,
- (c) API,
- (d) Government agencies,
- (e) National Electrical Code⁽⁵⁾ certifying agents, or
- (f) Other international standards associations

5.1.2.3 Selection and design of the CP system for optimum economy of installation, safety, maintenance, and operation.

5.1.2.4 Selection and specification of materials and installation practices that ensure dependable service for the operating life of the CP system.

5.1.2.5 Selection of a system to minimize excessive protective current densities or excessive earth (sea) potential gradients that may have detrimental effects on coatings or on neighboring buried or submerged foreign structures.

5.1.2.6 Initiation of cooperative investigations to evaluate the possible effects of the proposed CP system on the facilities of others (or their future expansion) in the general proximity.

5.2 Major Objectives of CP System Design

5.2.1 To deliver sufficient current for the design life of the facility, protect the structure, and distribute the current so that the selected criterion for CP can be efficiently satisfied.

5.2.2 To minimize the effect on associated pipelines or other neighboring metallic structures that may be caused by the operation of the proposed system.

5.2.3 To provide anode system design life commensurate with the design life of the protected structure or plan, and, when necessary, provide adequate rehabilitation procedures and appurtenances for the anode system.

⁽⁵⁾ National Fire Codes, National Electrical Code 70 (Quincy, Massachusetts: National Fire Protection Association).

5.2.4 To provide adequate allowance for anticipated changes in structure current requirements and anode current delivery capability from the standpoints of aging, additions to the structure, and possible changes in the environment.

5.2.5 To place all CP system components such that the possibility of disturbance or damage is minimal.

5.3 Information Necessary or Useful for Offshore Structure CP System Design

5.3.1 Structure construction specifications and practices:

- (a) Construction drawings,
- (b) Onshore construction site, offshore construction practices, and probable construction dates,
- (c) Number, size, and locations of riser pipes, including electrical cables,
- (d) Coatings,
- (e) Availability of electrical power,
- (f) Corrosion control measurement points (test stations, electrical bond locations, etc.),
- (g) Safety requirements,
- (h) Installation accessibility and availability of structure equipment for possible use in system installation and/or replacement,
- (i) Anticipated life of structure (design life),
- (j) Water level,
- (k) Pile guides removed after piling is completed or included in the CP design, and
- (l) Location of isolation flanges or standoffs.

5.3.2 Offshore site conditions:

- (a) Water depth, oxygen content, velocity, turbulence, temperature, water resistivity, tidal effects, silt, sand, and suspended solids (see Appendix A),
- (b) Dependability of future monitoring and maintenance, including cost factors,
- (c) Adjacent facilities, including pipelines,
- (d) Existing and proposed CP systems, and
- (e) Electrical isolation from foreign pipelines or structures.

5.3.3 Field survey data, corrosion test data, and operating experience:

- (a) Protective current requirements to meet applicable criterion or criteria (see Paragraph 5.6),
- (b) Water resistivity (considering possible stratification of water properties),
- (c) Changes in construction specifications,
- (d) Electrical isolation and/or continuity,
- (e) Interference currents (see Section 7),
- (f) Performance history of previous or existing CP systems in the same general environment,
- (g) Maximum operating temperatures of pipeline risers, and
- (h) Other maintenance and operating data.

5.3.4 Complete field survey work prior to actual application of CP is not always required if previous experience and test data are available for estimating current requirements and system performance.

5.4 Types of CP Systems

5.4.1 Galvanic anode systems

5.4.1.1 Galvanic anodes may be alloys of such active metals as magnesium, zinc, or aluminum. These alloys can be obtained in a variety of shapes and sizes to deliver protective current to a specific offshore structure with optimum current distribution. The method used to attach the anodes to the structure should be governed by their type and application, but low-resistance electrical contact must be maintained throughout the operating life of the anodes.

5.4.1.2 The performance of galvanic anodes in seawater depends critically on the composition of the alloy, particularly in the cases of zinc and aluminum (see Appendix B).

5.4.1.3 Magnesium anodes are very active and furnish high current outputs. For this reason, they can provide CP with a minimum number of anodes. Because of their properties, they usually are not used for long-life designs.

5.4.1.4 For coated structures, the galvanic anode material should be capable of supplying current even after many years of very low anodic current density.

5.4.2 Impressed current anode systems

5.4.2.1 Impressed current anode materials may include lead-silver alloy, platinum over various substrates, mixed metal oxides, lead-platinum, graphite, or silicon-iron. These anodes should be connected with an electrically insulated conductor, either singly or in groups, to the positive terminal of a direct current source such as a rectifier or generator. The structure to be protected should be connected to the negative terminal of the direct current source.

5.4.3 Combination of galvanic anode and impressed current systems

5.4.3.1 A combination CP system provides protection during structure construction and/or during times when the impressed current system is inoperative.

5.4.3.2 If the galvanic portion of the system is smaller than a conventional long-term system, it requires careful design to ensure adequate amount and distribution of current.

5.5 Considerations That Influence Selection of the Type of CP System

5.5.1 Availability of electrical power

5.5.2 Dependability of the overall system

5.5.2.1 Galvanic anode systems have shown dependability for long-term protection.

5.5.2.2 Impressed current systems are capable of providing long-term protection but are less tolerant of design, installation, and maintenance shortcomings than galvanic anode (sacrificial) systems. Good service can be expected if proper attention is paid to mechanical strength, connections, cable protection (particularly in the wave or splash zone), choice of anode type, and integrity of power source. Adequate system monitoring should be provided.

5.5.2.3 Built-in redundancy, the use of appropriate design margins, and provisions at the design stage for thorough maintenance can enhance the dependability of an impressed current system.

5.5.3 Total protective current required

5.5.4 Given the current required, the feasibility of protection with galvanic anodes and selection of anode material can be established by consideration of the following (see Appendixes):

- (a) Resistivity of the electrolyte,
- (b) Anode-to-structure potential (when structure is at protected level),

(c) Freedom from mechanical damage in installation, launching, and operation,

(d) Useful life expectancy of anode material, and

(e) Structure weight and structural limitations.

5.5.5 The physical space available for impressed current anodes placed on the ocean floor should be determined by the proximity of other structures and pipelines and by future construction and maintenance considerations.

5.5.6 The economics of capital investment, maintenance, inspection, depreciation, taxes, and corrosion losses should be considered over the entire expected life of a CP system to assess the impact of the various alternatives properly.

5.5.6.1 A galvanic anode system requires a relatively large initial capital investment but little maintenance expense.

5.5.6.2 An impressed current anode system typically requires a lower initial capital investment with power and higher maintenance expenses added over the life of the system.

5.6 Factors Determining Total Current Requirements for CP

5.6.1 Total submerged areas:

5.6.1.1 Water-submerged area.

5.6.1.2 Area below mudline.

5.6.1.3 On structures that may contain wells, the actual anticipated number of conductors to be installed.

5.6.1.4 Uninsulated and unprotected foreign structures.

5.6.2 Anticipated minimum protective design (or maintenance) current density requirements of submerged structure area.

5.6.2.1 Typical long-term average water zone current densities for CP of open-ocean structures that have been employed historically range from 55 to 430 mA/m² (5 to 40 mA/ft²). For values typical of 11 offshore production areas, see Appendix A. Alternatively, based on service data from offshore structures and laboratory results from test specimens, Hartt and Lemieux¹⁰ proposed that design mean current density, i_m , conform to the expression used in Equation (1):

$$i_m = \frac{10^{(a+c\sigma)} \times T_d}{b+1} \quad (1)$$

where:

- σ = standard deviation for the i_m data,
- T_d = design life
- c = safety factor multiple on σ , and
- a and b are constants.

Values for a , b , and σ were determined for cold and warm water locations as listed in Table 1. The

magnitude for c is selected based on the factor of safety that is judged appropriate with credit being given for system redundancy. It was shown that the design i_m values in Appendix A for cold water locations correspond to $c \sim 1$, whereas the Appendix A current densities exceed the i_m projected by Equation (1) for warm water locations even with $c = 2$, which encompasses 97.5% of the data.

Table 1: Suggested Design Parameters for Equation (1)

	Warm/Shallow Parameters	Cold/Deep Water Parameters
σ	0.233	0.229
a	3.130	2.820
b	-0.410	-0.226

5.6.2.2 Typical mud zone protective current densities are 10 to 30 mA/m² (1 to 3 mA/ft²).

5.6.2.3 An allowance should be included in the total design current requirements to compensate for the current load imposed by the well casings below the mudline. Values typically range from 1.5 to 5 A per well. For tension leg platform (TLP) and subsea production templates the well casings may be coated or cemented from total depth (TD) to the seabed, and thus greatly reduce the bare steel areas that draw current. In these cases consideration for the reduced surface area should be made, which may justify a reduction in the current allowance per well.

5.6.2.4 An allowance should be included in the total design current requirements to compensate for the current load imposed by pilings below the mudline. Values typically range from 1.5 to 5 A per piling. For subsea templates, this current demand may control the design.

5.6.3 Allowance for coatings, if any, on submerged portions of the structure.

5.6.3.1 In the past, conventional protective coatings (other than anode shields) were seldom applied to structures below the splash zone. However, increased current requirements and anode weight restrictions can affect the decision to coat complex structures to be installed in deeper waters with higher current density requirements, in shielded areas such as large conductor bundles, and/or on structures with extended design lives.

5.6.3.2 The current demand of a coated structure increases with time as the coating deteriorates. Enough CP capacity should be provided to maintain protection as the coating deteriorates. Current demand may increase more or less rapidly than a visual inspection of the coating deterioration indicates.

5.6.3.3 Calcareous coatings, formed on the structure members by the application of CP current, reduce the current density required to maintain protective potentials and also improve current distribution (see Paragraph 5.6.4). Organic coatings also promote the formation of a dense calcareous deposit at coating holidays and bare areas because the initial current density may be relatively high at such locations. However, the solubility of potential film-forming calcareous deposits normally increases with decreasing temperature such that colder waters might not allow the formation of a protective calcareous coating or could require higher initial current density to achieve polarization.

5.6.4 Efficiency of current distribution

5.6.4.1 Current distribution efficiency can be improved by use of a greater number of anodes of lower individual output. Current distribution can also be improved by using a coating on the structure.

5.6.4.2 Galvanic anode systems, being made up of numerous distributed, small current sources (typically from 3 to 6 A each) achieve maximum efficiency of current distribution. When these anodes are mounted at least 30 cm (12 in.) offset from the structure members, a uniform current distribution is normally assumed for design purposes.

5.6.4.3 Impressed current anodes, being fewer in number and designed for larger current outputs than galvanic anodes, normally have a reduced current distribution efficiency. These anodes may be designed to discharge from 30 to more than 200 A each. The high current output usually results in overprotection of the nearest structure surfaces. To compensate for the inefficient distribution of current, an efficiency factor (usually in the range of 67 to 80%) should be used. The CP system should be sized to provide 1.25 to 1.50 times

the calculated total current requirement, using the surface areas and selected design current densities.

5.6.4.4 With either galvanic or impressed current systems, the anodes should be distributed vertically and/or horizontally in accordance with the calculated current requirements of the structure members. Computer modeling can be used to verify proper current distribution.

5.7 Factors Determining Anode Current Output, Operating Life, and Efficiency

5.7.1 Various anode materials have different rates of consumption when discharging a given current density from the anode surface in a specific environment. Therefore, for a given current output, the anode life depends on the anode material as well as on its weight. Established anode performance data should be used to calculate the probable consumption rate (see Appendixes B and C).

5.7.2 Galvanic anodes and anode systems should be designed to provide sufficient exposed anode area to produce the required protective current for the life of the anode system. Two alternative protocols for calculating anode output capability are shown in Appendixes D and E. The anode system must also provide sufficient weight of anode material to supply current for the desired number of years of protection, based on established anode performance data.

5.7.3 Proper design of a galvanic anode system must consider structure-to-anode potential and resultant anode current output and, when applicable, anode lead wire resistance. The net driving voltage between a typical aluminum-zinc-mercury or zinc anode of -1.50 V (Ag/AgCl [sw] reference) is only 0.25 V (1.05 - 0.80), although the initial net driving voltage is higher because the structure potential is more positive at this time.

The anode lifetime (L) of galvanic anodes may be determined using Equation (2):

$$L = \frac{W \times u}{E \times I} \quad (2)$$

where:

- L = effective lifetime of the anodes in years
- W = net mass of the anodes in kg or lb
- U = utilization factor determined by the amount of anode material consumed when the remaining anode material cannot deliver the current required
- E = consumption rate of the anode in kg/A-yr or lb/A-yr
- I = mean current output during the lifetime in A

The shape of the anode affects the utilization factor. Proper selection of length, diameter, and core diameter

can result in utilization factors ranging from 0.75 to almost 1.0. For standoff-type anodes, utilization factors of 0.90 to 0.95 are common. For bracelet anodes, values of 0.75 to 0.90 may be used.

5.8 Special Mechanical and Electrical Considerations

5.8.1 The performance of a CP system is dependent on the ability of the various components to withstand the physical stresses to which they are subjected. The type of system, the various components thereof, and the physical installation should all be durable and dependable.

5.8.2 Galvanic anode systems are relatively simple, but consideration must be given to the following:

5.8.2.1 Anodes should be located on the structure to ensure polarization of node welds as early as possible. Node welds are critical for structural strength of structures. Polarization of node welds is of primary importance to prevent development of unacceptable weld profiles such as undercutting in the heat-affected zone (HAZ) and pitting in the weld. Both types of corrosion cause additional stress concentration that can lead to fatigue cracking. Nodes are also zones of high metal surface area and complex geometry requiring greater current density for protection and to overcome the effects of shielding. Weld consumables that can cause welds to be anodic to the steel shall not be used. Tests shall be carried out as a part of the welding pre-qualification test (WPQT).

5.8.2.2 Anode cores must be structurally suitable for the anode weight and the forces to which the anode is subjected, both during structure setting and pile-driving operations and during storms and hurricanes. It is important that the core be able to withstand anticipated wave forces in the later stages of anode consumption, when the body of the anode is no longer adding its strength to that of the anode core.

5.8.2.3 The core should be designed to maintain electrical integrity with the anode body for the full design life of the anode. A large-diameter core aids in achieving the required electrical output toward the end of the life of the anode.

5.8.2.4 Reinforcement to the structure members may be required to support the larger sizes of galvanic anodes. If so, it should be made at the point of anode attachment by gussets, doubler plates, or another approved method.

5.8.2.5 Because the efficiency of some aluminum alloys is adversely affected when they are covered with mud, attaching such anodes to structures located at or below the mudline should only be done after testing the anode in representative mud, or if experience shows that the intended anode mater-

ial does not passivate when covered by mud. The reduction in the current output and efficiency from a galvanic anode covered by mud should also be considered if it is at or below the mudline.

5.8.2.6 Whenever practicable, the larger sizes of galvanic anodes should be attached to the structure in such a manner that stresses are minimized at the point of attachment.

5.8.2.7 When the larger offshore-type anodes are used, cracks may occur while cooling during casting because of the different coefficients of expansion of the anode and the core. These cracks are not detrimental, provided they do not converge in a manner to allow loss of anode material. Warpage is acceptable if it does not adversely affect the anode installation. More specific guidelines can be found in NACE Standard RP0387.¹¹

5.8.2.8 When galvanic anodes are mounted flush with the steel surface, either the back face of the anode or the surface of the steel should be coated or fitted with a dielectric shield to prevent premature consumption of the anode material from the back face and possible failure of the mount because of the pressure developed by the corrosion products of the anode.

5.8.3 Impressed current systems are more critical with respect to mechanical damage because relatively few anodes, each discharging a substantial amount of protective current, are involved. The loss of an anode can seriously reduce system performance.

5.8.3.1 The electrical connection between the anode lead cable and the anode body must be made watertight and mechanically sound.

5.8.3.2 Cable and connection insulating materials should be resistant to chlorine, hydrocarbons, and other deleterious chemicals.

5.8.3.3 Care must be taken to provide suitable mechanical protection for both the anode and its connecting cable. On suspended systems, the individual anodes or anode strings may be equipped with winches or other retrieval means as a damage-preventing measure during severe storms or for routine inspection and maintenance. The loss of protection during these periods should be considered.

5.8.3.4 Acceptable methods of installing fixed-type impressed current anodes include, but are not limited to, the following:

(a) Anodes can be installed at the lower ends of protective vertical steel pipe casings or conduits. Casings should be attached to above-water structure members and supported at repeating

members below water. The anodes should be lowered through the casings (which protect the anode lead wires) and should be allowed to extend below a termination fitting at the bottom of each casing. This method provides a means of anode retrieval or replacement using the anode cable, without diver assistance. Marine growth or corrosion scale may make anode retrieval difficult.

(b) Anodes with essentially flat configuration-mounted, insulating-type holders can be attached directly to submerged structure members or to auxiliary structural members, such as vertical pipes, which can be removed for anode replacement. Properly designed systems of the latter type permit anode retrieval without diver assistance.

(c) Anodes can be installed on submerged structure members using offset steel structural supports attached to the structure members. Diver assistance is required for this type of anode replacement.

(d) Anodes may be bottom-installed on the ocean floor in special instances, such as in Cook Inlet, Alaska. Anodes are typically mounted on specially designed concrete sleds for stability; this minimizes the possibility of their becoming covered with mud or silt. Steel reinforcing in the concrete has been reported to be subject to interference current corrosion.

5.8.3.5 Impressed current anodes should be located as far as practical from any structure member (usually a minimum distance of 1.5 m [5.0 ft], but proportional to current magnitude [see Paragraph 8.5.2]). If a spacing of 1.5 m (5.0 ft) is not feasible a dielectric shield should be used to minimize wastage of protective current by localized overprotection. Anode holders should be designed to avoid such wastage and to minimize the possibility of a short circuit between the anode and the structure. NOTE: Satisfactory performance of coating materials used as cathode shields has not been fully demonstrated over long periods of time. Providing a suitable anode-to-cathode spacing is the preferred method of ensuring good anode current distribution.

5.8.3.6 Simple, rugged, easily maintained impressed current equipment should be used. Because conditions at an offshore location seldom vary, except for weather-related factors, manually adjustable oil-cooled rectifiers with both alternating current (AC) and direct current (DC) overload protection are preferred. In certain special cases, either *constant current* or *automatic potential control* rectifiers may prove desirable, but the cost and maintenance of these units should be compared.

5.8.3.7 There may be a delay of several months to a year or more between the time a structure is

set until permanent electrical power becomes available. Plans should be made for either temporary power and early energizing of impressed current systems or a short-term galvanic anode system. Otherwise, serious corrosion of structure members, as well as the underwater components of the impressed current system, can occur.

5.9 Design Drawings and Specifications

5.9.1 Suitable drawings should be prepared to designate the overall layout of the CP system and the location of significant items of hardware, corrosion test and monitoring stations, bond boxes, insulators, and neighboring buried or submerged metallic structures.

5.9.2 Layout drawings should be prepared for each impressed current CP installation, showing details and location of its components with respect to the structure to be protected.

5.9.3 The locations of galvanic anodes should be shown on drawings or recorded in tabular form with appropriate notes as to anode type, weight, shape, and location.

5.9.4 Specifications should be prepared for all materials and installation practices to be incorporated in construction, inspection, and operation of the CP system.

5.9.5 Suitable, as-built drawings should be prepared during and at the completion of all installations. These drawings should include any deviations from original design.

5.9.6 Complete records should be maintained. Details of CP installations are necessary for trouble-shooting and future design (see Section 15).

5.10 Design of Companion Facilities

5.10.1 If the design of an offshore CP system incorporates the use of insulating flanges or unions, locating each insulating device in vertical piping minimizes internal shorting caused by accumulation of salts, metallic residue, or other conductive materials. Such insulating devices should not be located below the water line (see Paragraph 6.7.1).

5.10.2 The potential sparking hazard of insulating devices should be recognized and considered in the design and location of such devices.

Section 6: Installation of Cathodic Protection Systems

6.1 Introduction

6.1.1 This section recommends procedures for installing CP systems in accordance with design considerations outlined in Section 5.

6.2 Construction Specifications

6.2.1 All construction work performed on CP systems should be done in accordance with drawings and specifications. The construction specifications should be in accordance with procedures outlined in Sections 3, 4, and 5.

6.3 Construction Supervision

6.3.1 All construction work performed on CP systems should be done under the supervision of qualified personnel to verify that the installation is made in strict accordance with the drawings and specifications. Exceptions should be made only with the consent of the supervising corrosion specialist.

6.3.2 All changes from construction specifications should be noted on as-built drawings.

6.4 Galvanic Anodes

6.4.1 Inspection and handling

6.4.1.1 Specific guidelines can be found in NACE Standard RP0387.¹¹

6.4.1.2 Anodes should be inspected to ensure that dimensions and weight conform to design specifications and that any damage from handling does not affect application.

6.4.1.3 In the case of weld-on anodes, the steel cores should be inspected for conformance to specifications. If the anode cores have welded joints or connections, these should be inspected to ensure compliance with structure welding specifications.

6.4.1.4 When galvanic anode suspension cables are used for the lead wire, the cables should be inspected for strength, voltage drop, and good electrical contact with the anode. When separate suspension cables are used, care should be taken to ensure that anode lead wires are not in such tension as to damage the lead wires or connections.

6.4.1.5 If coatings are specified for anode supports or suspension cables, they should be visually inspected and repaired if damaged.

6.4.2 Installing anodes

6.4.2.1 Anodes should be installed according to construction specifications.

6.4.2.2 When anodes are welded directly to the structure, the welds should be inspected for conformance to the structure construction welding specifications.

6.4.2.3 Use of doubler and/or gusset plates should be considered for anodes mounted on standoff pipe cores and weighing more than 230 kg (500 lb).

6.4.2.4 Doubler and/or gusset plates may be installed on anode supports at the time of anode installation. If installed as part of the anode fabrication, these plates may be subject to serious damage during anode hauling and handling.

6.4.2.5 Suspended galvanic anodes should be installed after the structure is set on location offshore, and the anode cables should be tested for good electrical contact to the structure after installation.

6.5 Impressed Current Systems

6.5.1 Inspection and handling

6.5.1.1 The rectifier or other power source should be inspected to ensure that internal connections are mechanically secure and that no damage has occurred during shipping and handling. Nameplate and actual rating of the direct current power source should comply with construction specifications.

6.5.1.2 Impressed current anodes should be inspected for conformance to specifications for anode material and size and length of lead wire and to ensure that the anode cap (if specified) is secure. Lead wires should be carefully inspected to detect possible insulation defects. Defects in the lead wires and/or anode caps must be properly repaired or the anode must be rejected.

6.5.1.3 Care should be exercised in handling all impressed current system components prior to final installation.

6.5.2 Installation provisions

6.5.2.1 A rectifier or other power source should be installed out of the way of operational traffic and remote from areas of extreme heat or likely contamination by mud, dust, water spray, etc. In areas in which two or more rectifiers are installed, the rectifiers should be spaced for proper flow of cooling air.

6.5.2.2 Wiring to rectifiers shall comply with any applicable regulatory codes and with the oper-

ator's specifications. An external disconnect switch in the AC wiring to the rectifier should be provided. The rectifier case shall be properly grounded. Connecting the negative to the case prevents inadvertent reversal of polarity.

6.5.2.3 On thermoelectric generators, a reverse current device should be installed to prevent galvanic action between the anode and structure if the flame is extinguished.

6.5.2.4 Impressed current anodes should be installed in accordance with construction specifications. Special care should be taken to avoid damage to anodes and their lead wires during installation. Careful supervision of this phase is most essential to proper long-term performance of the CP system.

6.5.2.5 Conductor cable connections to the rectifier from the anode(s) and the structure must be mechanically secure and electrically conductive. Before the power source is energized, verification should be made that the negative (-) conductor is connected to the structure to be protected, that the positive (+) conductor is connected to the anode(s), and that the system is free of short circuits.

6.5.2.6 Connection between the positive header cable and lead wire(s) from the anode(s) should be mechanically secure and electrically conductive. The connections must be sealed to prevent moisture penetration and ensure electrical isolation from the environment. Submerged connections require seals suitable for the water pressures and environment to which they may be subjected.

6.5.2.7 When installing a suspended anode for which separate suspension is required, care should be taken that the lead wire is not in such tension as to damage the anode lead wire or connections.

6.5.2.8 Operating personnel should be trained in the function and need for such a system to ensure continued energization of the system.

6.6 Corrosion Control Test Stations, Connection, and Bonds

6.6.1 Installation provision

6.6.1.1 Test leads to pipelines associated with offshore structures must be mechanically secure and electrically conductive and should be readily accessible.

6.6.1.2 Both the pipe and the test lead wires should be clean, dry, and free of foreign material at points of connection when the connections are

made. The complete connection should be coated to prevent atmospheric corrosion.

6.6.1.3 Conductive connections to other pipelines or across insulating joints should be installed in accordance with Paragraph 6.6.1.1. All bond connections should be readily accessible for testing. Cables should have welded connections. Care should be taken to ensure that all parts of the structure are in proper electrical contact with one another or are equipped with separate anodes.

6.7 Other Considerations

6.7.1 Insulating devices

6.7.1.1 Use of insulating flanges in pipelines associated with structures is covered in Paragraph 5.10.1. If insulating flanges above water are inaccessible, extension test leads should be installed in accordance with Paragraph 6.6.1.1 for test or bonding purposes.

Section 7: Control of Interference Currents

7.1 Introduction

7.1.1 The purpose of this section is to describe the possible detrimental effects of interference currents, sometimes called stray currents, and to recommend practices for their control.

7.1.2 Except during certain types of welding operations, the possibility of interference current corrosion on offshore structures is minimal.

7.2 Effects

7.2.1 Corrosion occurs in areas at which the interference current leaves the affected structure and enters the electrolyte as it returns to its source.

7.2.2 The degree of damage is directly related to:

- (a) the quantity of interference current and the current density,
- (b) the area of the affected structure where the current leaves to enter the electrolyte, and
- (c) the period of time when this effect occurs.

7.3 Short-Term Interference

7.3.1 The most common serious cause of short-term interference to a structure is welding operations when the welding machine is mounted on a barge or vessel with the machine's negative terminal grounded to the vessel and with the electrodes positive. Some operators have reported serious damage to structures with complete penetration of the submerged member as a result of welding current interference. The following measures should be implemented to prevent interference current during welding operations from a barge moored alongside during construction: (a) All welding machines should be electrically isolated from the barge, and (b) the grounding cable from each machine should be connected to the structure. Alternatively and preferably from a corrosion standpoint, the barge oper-

ator should place the welding machines on the structure.

7.3.2 When negative welding leads are bonded to the structure, current return is ostensibly through negative leads or cables connected to the structure, but is also to some degree through the parallel water path from structure to barge hull if the precautions of Paragraph 7.3.1 are not followed. Current return through the water can be reduced by decreasing the resistance of the negative cables, by increasing their number and/or diameter, and by decreasing their length. Negative cables should be connected to the structure at a point as close to the barge as possible.

7.4 Long-Term Interference

7.4.1 There are normally no long-term interference sources that would cause significant corrosion on a structure, if all components of the structure are properly bonded.

7.4.1.1 The submerged, bare structure area is usually very large with respect to exposed pipeline areas; consequently, pipeline protection currents have a negligible interference effect on the structure.

7.4.1.2 The location of interference current sources and the physical arrangement of a protected structure are usually such that there is no tendency for significant interference to exist.

7.4.2 In certain cases, interference may be produced on a foreign pipeline when it is electrically isolated from a protected structure, because of the structure's CP system. Such interference can readily be controlled by the use of a current drainage bond from the pipeline to the structure, by installing CP on the isolated pipeline, or by upgrading the existing CP system on the pipeline. These mitigation procedures should be performed in cooperation with other companies or operators, when applicable.

Section 8: Dielectric Shields

8.1 Introduction

8.1.1 This section recommends practices for the selection and use of dielectric shields, including shield configurations and materials, for CP of structures.

8.2 General

8.2.1 The objective of dielectric shields, and coatings used as dielectric shields, is to prevent extremely high current densities and current wastage in the vicinity of the anodes. This serves to promote more uniform protective current distribution.

8.3 Use of a Dielectric Shield

8.3.1 Use of a dielectric shield depends on the CP design (see Section 5). Typically, dielectric shields are used in conjunction with an impressed current system because higher voltage gradients are generally used in such systems. A dielectric shield may also be used with a high-potential galvanic anode such as magnesium.

8.3.2 Specific uses of dielectric shields, including coatings used as dielectric shields, are as follows:

- (a) to cover cathode surfaces adjacent to anodes,
- (b) to provide a nonconducting extension to steel pipe conduits for impressed current anodes,
- (c) to afford a backing for flush-mounted galvanic anodes,
- (d) to minimize current demand by structure members in highly congested areas, and

(e) to restrict anode current output, i.e., reduce wastage of anode current to the structure in the immediate vicinity of the anode.

8.3.3 A general underwater coating may be considered as a type of dielectric shield and can be used either to reduce the required current or to extend the life of a CP system.

8.4 Types of Dielectric Shields

8.4.1 Various dielectric shields have been used in structure CP. These include yard-applied coatings, prefabricated plastic or elastomeric sheets, plastic pipe sleeves, and coated standoffs or supports for impressed current anodes.

8.5 Design Considerations

8.5.1 Electrochemical reactions at the anode and cathode produce corrosives and gases that may attack the dielectric shield or cause disbonding by gas formation under the dielectric shield. Materials selected should be suitable for the intended service.

8.5.2 For proper performance, the design of the dielectric shield (radius around the anode or distance from the anode to the nearest bare cathode surface) must involve considerations of the anode current output, the water resistivity, the geometry of the structure, and the location of other anodes.

8.5.3 Mechanical damage from environmental factors such as wave forces, water currents, floating debris, ice, and marine organisms must be considered. The design shall also include allowances for possible handling damage prior to structure placement.

8.5.4 The anticipated life or general deterioration of any dielectric shield material should be considered in the CP design (see Paragraph 5.8.3.4).

Section 9: Operation and Maintenance of Cathodic Protection Systems

9.1 Introduction

9.1.1 This section designates procedures for energizing and maintaining continuous, effective, and efficient operation of CP systems.

9.2 Electrical Measurements

9.2.1 Electrical measurements and inspections are necessary to determine that protection has been established according to applicable criteria and that each

part of the CP system is operating properly. Conditions that affect protection are subject to change with time. Corresponding changes are required in the CP system to maintain protection. Periodic measurements and inspections are necessary to detect performance changes in the CP system.

9.2.2 Care should be exercised in selecting the location, number, and type of electrical measurements used to determine the adequacy of CP (see Section 4).

9.2.3 Conditions may exist in which operating experience indicates that surveys and inspections should be made more frequently than recommended herein, such as following severe storms.

9.3 A survey should be conducted after each CP system is energized to determine whether it satisfies applicable criteria and operates effectively. This survey must include structure potential measurements in sufficient detail to demonstrate conclusively that protection has been attained (see Section 4).

9.4 A periodic survey should be made to ensure the continuity of CP. The electrical measurements used in this survey should include structure potential measurements at locations selected for the earlier survey(s). The period between surveys should be determined as follows:

9.4.1 If previous survey data are not available, or no analysis of the previous data has been carried out, the survey should be carried out annually.

9.4.2 For sacrificial anode CP systems there are two critical periods of operation—initial operation of the system, demonstrating that the entire structure is polarized (see Paragraph 9.3); and final years of design life of the system, when the performance of the anodes can become more difficult to predict. Between these periods structure potentials and anode wastage rates follow well-defined trends. Taking this into account, a risk-based approach to CP inspection can be adopted. Inspection frequency should be based on a five-year interval unless more frequent inspection is required because of any of the following conditions being present:

- Visual inspection reveals additional steelwork on the structure not included in the current structure CP drawings. This could include debris in electrical contact with the structure, new conductors, new caissons, new risers, etc. A CP survey should be carried out immediately, structure potentials measured, structure CP drawings updated, the impact on the structure anode design life assessed, and the need for any remedial work assessed (e.g., removal of debris, installation of additional anodes, etc.).
- Anodes are within two years of the end of their original design life. The CP survey should be carried out annually. If the required structure life is in excess of the remaining anode design life, the actual remaining life of the anode system should be reassessed (based on a survey of potentials and remaining anode mass) and the need for a retrofit assessed. If the original CP design was conservative, the actual remaining anode life may be well in excess of two years. This actual

remaining anode life can be used in scheduling future CP surveys (on the same five-year/two-year basis).

- Local regulatory requirements that require more frequent inspections (e.g., U.S. Minerals Management Service⁽⁶⁾—annual).

9.4.3 For impressed current cathodic protection (ICCP) systems the initial operation of the system is critical, demonstrating that the entire structure is polarized (see Paragraph 9.3). After this, the performance of the ICCP system depends on proper operation and maintenance (see Paragraph 9.5). Taking this into account, a risk-based approach to CP inspection can be adopted. Inspection frequency should be based on a five-year interval unless more frequent inspection is required because of any of the following conditions being present:

- Visual inspection reveals additional steelwork on the structure not included in the current structure CP drawings. This could include debris in electrical contact with the structure, new conductors, new caissons, new risers, etc. A CP survey should be carried out immediately, structure potentials measured, structure CP drawings updated, the impact on the ICCP system assessed, and the need for any remedial work assessed (e.g., removal of debris, installation of additional anodes, modified anode currents, etc.).
- Operation and maintenance of the ICCP shows poor functionality, which indicates damaged anodes or cables
- Local regulatory requirements that require more frequent inspections (e.g., U.S. Mineral Management Service—annual).

9.5 Inspection and tests of ICCP facilities should be made to ensure their proper operation and maintenance.

9.5.1 All sources of impressed current should be checked at intervals not to exceed two months. Evidence of proper functioning may be current output, normal power consumption, or satisfactory structure-to-seawater potentials on the protected structure.

9.5.2 All ICCP facilities should be inspected annually as part of a preventive maintenance program to minimize in-service failure. Inspection may include a check for electrical shorts, satisfactory ground and header cable connections, meter accuracy, rectifier efficiency, and overall circuit resistance.

⁽⁶⁾ Bureau of Mines, 2402 E Street NW, Washington, DC 20241.

9.6 The test equipment used for obtaining each electrical value should be maintained in good operating condition and checked annually for accuracy. Reference electrodes should be checked more frequently for possible inaccuracy because of contamination, bad electrical connections, or deterioration of wire insulations.

9.7 Diver-assisted or ROV inspections may be conducted in conjunction with other underwater work to ensure that the CP system is effective.

9.8 Remedial measures should be taken promptly when periodic surveys and inspections indicate that protection is

no longer adequate or will soon become inadequate. These measures may include:

9.8.1 Repairing, replacing, or adjusting components of CP systems.

9.8.2 Providing supplementary CP facilities in areas where additional protection is necessary.

9.8.3 Repairing defective insulating devices or continuity bonds.

Section 10: Splash Zone Corrosion Control Measures

10.1 Introduction

10.1.1 This section lists corrosion control measures that minimize the deterioration of steel members in the splash zone. Some procedures may not be applicable in all areas of the world because of varying service conditions.

10.1.2 Corrosion of attached pipelines or risers in the splash or submerged zone is outside the scope of this standard.

10.1.3 Additional thickness of steel is usually provided in the splash zone.

10.2 Placement

10.2.1 Unless the setting depth of the structure can be ensured, consideration should be given to additional protection beyond the normal splash zone interval to provide a margin of safety.

10.3 Steel Wear Plates and Corrosion Allowance

10.3.1 Wear plates should compensate for the anticipated corrosion and wear during the life of the structure. Wear plates are usually 13 to 19 mm (0.50 to 0.75 in.) thick.

10.3.2 Wear plates are needed because damage can occur to coatings or sheathings used in the splash zone.

10.3.3 In addition to providing a corrosion allowance, wear plates add stiffness and strength, thereby providing greater impact resistance.

10.3.4 Wear plates are usually coated or sheathed for additional corrosion protection.

10.3.5 Corrosion allowance by additional steel thickness may be used instead of wear plates. The thickness should be calculated based on estimated lifetime of the installation and anticipated corrosion rate. It is normally not less than 6 mm (0.25 in.). The corrosion rate in the splash zone is typically in the range 0.2 to 0.4 mm (0.007 to 0.015 in.)/year.

10.4 Alternative Corrosion Control Measures for Steel in the Splash Zone

10.4.1 UNS⁽⁷⁾ N04400 (Nickel-copper alloy 400) or UNS C70600 (90/10 copper-nickel alloy) sheathing

10.4.1.1 UNS N04400 sheathing, typically 1 to 5 mm (40 to 200 mils) thick (18 to 4 AWG,⁽⁸⁾ or UNS C70600 sheathing, typically 4 to 5 mm (160 to 200 mils) thick, should be attached to tubular members in the splash zone either by banding or welding. Welding is preferred because the annulus between the steel member and the sheathing is sealed.

10.4.1.2 The metal sheathing should be protected from impact damage. Alloy-clad steel plate may aid in preventing damage.

10.4.2 Vulcanized chloroprene

10.4.2.1 Vulcanized chloroprene is typically applied in thicknesses of 6 to 13 mm (0.25 to 0.50 in.).

⁽⁷⁾ Metals and Alloys in the Unified Numbering System (latest revision), a joint publication of ASTM International and the Society of Automotive Engineers (SAE), 400 Commonwealth Drive, Warrendale, PA 15096.

⁽⁸⁾ American Wire Gauge (AWG): A particular series of diameters and thicknesses established as a standard in the United States and used for nonferrous sheets, rods, and wires. Also known as the Brown and Sharpe Gauge.

10.4.2.2 Because this coating cannot be applied in the fabrication yard, it is normally restricted to straight runs of tubular members.

10.4.2.3 A minimum of 50 mm (2.0 in.) should be left uncoated at each end of a tubular member to prevent damage to the chloroprene during the welding operations.

10.4.3 High-build organic coatings

10.4.3.1 These coatings are usually filled with silica glass-flake or fiberglass.

10.4.3.2 These coatings are typically applied to thicknesses of 1 to 5 mm (40 to 200 mils) over an abrasive blast-cleaned surface.

10.4.3.3 Because this coating may be applied in the fabrication yard after assembly, joints may be protected as well as straight tubular runs.

10.4.3.4 To improve inspection possibilities, an antifouling coating may be applied on the coated members. Antifouling coatings are effective up to about 10 years.

10.4.4 High-performance structure coating systems 250 to 500 μ m (10 to 20 mils)

10.4.4.1 Although some high-performance coating systems currently used to protect the atmospheric zone have performed reasonably well in the splash zone, they are not suited as a primary control measure for long-life structures.

10.4.5 Heat-shrink sleeves. NOTE: Heat-shrink sleeves have not performed well in the North Sea.

10.4.5.1 Heavy plastic sleeves that shrink when exposed to an elevated temperature and are pre-coated internally with a sealant adhesive have been used to protect straight tubulars in the splash zone. If the sleeve is slightly damaged, the visco-elastic nature of the sealant in combination with

the remaining radial shrink forces of the sleeve causes the sealant to flow to the damage site and effectively seal over the damage. Surface preparation to remove rust and coarse roughness is required.

10.4.6 Thermal-sprayed aluminum

10.4.6.1 Thermal-sprayed aluminum (either flame or arc) applied to 200 μ m (8 mils) and sealed with a silicone sealer have been used in the splash zone. Good surface preparation and cleanliness are essential. The coating should be applied in a minimum of two passes. The sealer seals the porosity of the coating and enhances service life and appearance. U.S. Military Specification MIL-STD-2138¹² offers guidelines for application and quality control.

10.4.6.2 Coating adhesion should exceed 7,000 kPa (1,000 psi). Laboratory adhesion tests may be performed using ASTM C 633.¹³ Field testing for adhesion may be performed with commercial instruments.

10.4.6.3 Thermal-sprayed aluminum has also been used in submerged and marine atmospheric services. For submerged areas this system is a candidate for areas in which protective CP potentials may be difficult to achieve, such as the underside of clamps and other geometrically shielded areas.

10.4.7 Petrolatum/wax-based tape systems

10.4.7.1 Petrolatum/wax-based coating systems with appropriate jacketing for mechanical protection may be employed.

10.4.7.2 Proper consideration shall be given to the mechanical stresses to be encountered in service by the coating system, and the protective jacketing system shall be selected to assure adequate mechanical protection.

Section 11: Maintenance of Splash Zone Corrosion Control Measures

11.1 This section lists inspection procedures and follow-up maintenance necessary to ensure continued protection of the structural steel located in the splash zone.

11.2 Inspection

11.2.1 The splash zone interval should be visually inspected annually to determine whether corrosion control is still effective. If failure has occurred, the extent of

damage to underlying structural members should be assessed and corrective action taken.

11.2.2 When wear plates are used and the protective coating system has either deteriorated or been mechanically damaged, periodic wall thickness measurements should be made to determine that the loss does not exceed the corrosion allowance.

11.3 Repair Methods

11.3.1 UNS N04400 sheathing

11.3.1.1 Tears in the UNS N04400 sheathing should be trimmed and repaired by welding or banding a UNS N04400 patch to the affected area.

11.3.1.2 An alternative procedure, which can also be performed at the water line, involves blast cleaning the damaged area after trimming the torn UNS N04400 and hand applying a thick coat of polysulfide rubber with air cure accelerator or splash zone barrier compound. The latter is a polyamide-cured epoxy formulated to displace water and cure underwater. If the area is exposed to wave action, it may be necessary to hold these compounds in place with wire mesh or burlap until the cure is complete

11.3.2 Vulcanized chloroprene

11.3.2.1 The procedure outlined in Paragraph 11.3.1.2 should be followed.

11.3.3 High-build organic coatings

11.3.3.1 Damaged areas may be repaired by spray or hand application of the original coating to an abrasive blast-cleaned surface or as outlined in Paragraph 11.3.1.2.

11.3.4 Heat-shrink sleeves

11.3.4.1 The steel surface should be cleaned, and any sharp projections should be removed.

11.3.5 Fiberglass wraps with water-activated resin

11.3.5.1 The steel surface should be cleaned to remove marine growth, and any sharp projections should be removed.

11.3.5.2 This system may use an initial sealer wrap to isolate the steel surface from seawater effectively. The outer fiberglass wrap provides a mechanical barrier.

11.3.6 Mastic-backed rubber wraps

11.3.6.1 The steel surface should be cleaned to remove marine growth, and any sharp projections should be removed.

Section 12: Surface Preparation

12.1 Introduction

12.1.1 This section recommends procedures for the proper surface preparation of structural steel shapes to be coated for service in the atmospheric zone of fixed offshore structures.

12.2 General

12.2.1 The objectives of surface preparation for steel in the atmospheric zone are to provide the necessary degree of cleanliness and the specified anchor pattern required for the designed coating system.

12.2.2 Automated blast-cleaning machines are economically desirable as a means of preparing plate, beams, and tubular members prior to fabrication.

12.2.3 The completed structure should be inspected to locate damaged or improperly primed areas prior to topcoating. Damaged areas and all weld areas require spot blasting and priming with the same material prior to completing the coating system.

12.2.4 All surface imperfections such as slivers, laminations, welding flux, weld spatter, and underlying mill scale exposed before or during operations shall be removed prior to surface preparation.

12.2.5 Surface preparation performed outside should be completed during daylight hours with the surface temperature above the dew point for that day, early enough to permit proper priming of the surface prior to the development of any moisture or flash rusting of the prepared surface. Tests for soluble salts should be performed prior to coating when the presence of any soluble salt on the prepared surface is suspected.

12.2.6 At the time of surface preparation or priming the surface temperatures shall be 3°C (5°F) or more above the dew point. Under no condition should a steel surface be conventionally coated while it is damp or wet.

12.2.7 If properly performed with containment, wet abrasive blasting may provide adequate surface preparation and reduce the dust problem created by dry blasting. However, if this type of cleaning is used, the coating systems must be compatible with the rust inhibitor used in the water blasting system. The surface prepared for coating must be dry and contaminant-free prior to coating.

12.2.8 Solvent or detergent degreasing shall be performed in accordance with SSPC⁽⁹⁾ SP 1.¹⁴

⁽⁹⁾ SSPC: The Society for Protective Coatings, 40 24th St., 6th Floor, Pittsburgh, PA 15222-4656.

12.2.9 Hand cleaning should be discouraged and should be used only for small areas where other methods of surface preparation cannot be used. Methods resulting in polishing of the steel surface, e.g., wire brushing, shall not be used.

12.3 NACE Surface Preparation Standards

12.3.1 The selection of the degree or grade of surface preparation should be determined by the requirements of the coating selected. Following are descriptions of the four degrees of abrasive blast-cleaned surfaces as given in joint NACE/SSPC standards.

12.3.1.1 NACE No. 1/SSPC SP 5¹⁵ states that a white metal blast-cleaned surface, when viewed without magnification, shall be free of all visible oil, grease, dust, dirt, mill scale, rust, coating, oxides, corrosion products, and other foreign matter.

12.3.1.2 NACE No. 2/SSPC SP 10¹⁶ states that a near-white metal blast-cleaned surface, when viewed without magnification, shall be free of all visible oil, grease, dust, dirt, mill scale, rust, coating, oxides, corrosion products, and other foreign matter. Random staining shall be limited to not more than 5% of each unit area of surface (approximately 58 cm² [9.0 in.²]), and may consist of light shadows, slight streaks, or minor discolora-

tions caused by stains of rust, stains of mill scale, or stains of previously applied coating.

12.3.1.3 NACE No. 3/SSPC SP 6¹⁷ states that a commercial blast-cleaned surface, when viewed without magnification, shall be free of all visible oil, grease, dust, dirt, mill scale, rust, coating, oxides, corrosion products, and other foreign matter. Random staining shall be limited to no more than 33% of each unit area (approximately 58 cm² [9.0 in.²]) of surface and may consist of light shadows, slight streaks, or minor discolorations caused by stains of rust, stains of mill scale, or stains of previously applied coating.

12.3.1.4 NACE No. 4/SSPC SP 7¹⁸ states that a brush-off blast cleaned surface, when viewed without magnification, shall be free of all visible oil, grease, dirt, dust, loose mill scale, loose rust, and loose coating. Tightly adherent mill scale, rust, and coating may remain on the surface. Mill scale, rust, and coating are considered tightly adherent if they cannot be removed by lifting with a dull putty knife.

12.3.1.5 A cross-index of various surface preparation standards is provided in Table 2.

Table 2: Surface Preparation Standards

Standard	White	Near-White	Commercial	Brush-Off
NACE	No. 1	No. 2	No. 3	No. 4
SSPC	SP 5	SP 10	SP 6	SP 7
ISO ^(A) 8501-1 ¹⁹	Sa 3	Sa 2-1/2		Sa 1

^(A) International Organization for Standardization (ISO), 1 rue de Varembe, Case Postale 56, CH-1121 Geneve 20, Switzerland.

12.4 Centrifugal Wheel Cleaning—This method is applicable to a fabrication plant where new weldments can be processed through an automated, wheel-type machine using metal abrasives. The cost of wheel blast surface preparation is significantly lower than the cost of air blast surface preparation work.

12.4.1 *Good Painting Practice, SSPC Painting Manual*,²⁰ should be referred to for centrifugal blast cleaning.

12.4.2 Special consideration should be given to:

12.4.2.1 Abrasive material—Steel grit of the appropriate mesh size and hardness should be used to produce the required surface profile using

the equipment selected to perform the work. Steel shot is not recommended for surface preparation for coatings to be used in severe surface applications.

12.4.2.2 Surface profile tests should be conducted and recorded on a regular agreed basis to ensure that the prepared surface of the components meets the cleanliness and profile requirements of the coating to be applied.

12.5 Air Blast Cleaning—This method is used when components are not suitable for the available automated machines, when cleaning is performed on the job (field) location, or when maintenance work is performed on offshore structures. Abrasives used are described in Paragraph 12.5.2.

12.5.1 Air supply—Initial inspection of the air supply should include the following:

12.5.1.1 Air supply capacity shall be sufficient to obtain 690 kPa (100 psi) air pressure at all operating nozzles.

12.5.1.2 Compressor shall be equipped with all properly operating safety equipment required.

12.5.1.3 Oil/moisture separators with properly maintained filters must be used in air lines. These shall be tested at least once each shift in accordance with ASTM D 4285.²¹

12.5.2 Abrasives—The blast-cleaning abrasive used for surface preparation shall be limited to the type specified in the contract documents and shall be of appropriate size to produce the required profile using the equipment available for the job. The abrasive must be clean and graded to a uniform standard size. See *Good Painting Practice, SSPC Painting Manual*.²⁰

12.6 Safety equipment for surface preparation should include, but shall not be limited to, the following:

- (a) Bureau of Mines⁽¹⁰⁾ or equivalent agency-approved air-fed blast hood, properly fitted, with good vision,
- (b) Charcoal-filtered and regulated compressed breathing air supply,
- (c) Operator-controlled deadman remote control valves,
- (d) Operator protective clothing, gloves, etc.,
- (e) Operator safety belts,
- (f) Proper scaffolding, and
- (g) Proper lighting.

12.6.1 Air blast operators must have proper training for effective operation of surface preparation and safety equipment.

Section 13: Coatings

13.1 Introduction

13.1.1 This section outlines general considerations relating to structure coatings and lists the generic composition of the coatings commonly used by offshore operators.

13.2 General

13.2.1 Conventional paints, surface preparation, and methods of application should not be used in extremely corrosive offshore environments. Because the maintenance cost on location is extremely high, only high-performance protective coating systems should be specified. Proper application and performance requirements of these systems demand rigorous surface preparation (see Section 12) and skilled craftsmanship in coating application and inspection (see Section 14). This can be achieved only through the enforcement of detailed and complete job specifications.

13.2.2 Proper application of high-performance coating systems requires that personnel observe and adhere to all applicable safety rules and regulations.

13.3 Coating Systems

13.3.1 Offshore coating systems are normally composed of primer, intermediate, and finish coats. Many generic coating materials are available but only a few

are considered by many owners and coating consultants to be suitable for offshore service.

13.3.2 Most coating systems are based on a highly inhibited prime coat designed to have superior wetting and adhesion properties to retard undercutting by rust, and to passivate the surface. Commonly used prime coats include:

13.3.2.1 Wash primers—These are conversion coatings consisting of a vinyl butyrate resin solvent solution, pigmented with zinc or strontium chromate. Prior to application, these coatings are mixed with a second component consisting of a solution of alcohol and phosphoric acid. They are applied as very thin films not to exceed 13 µm (0.50 mil) dry. On contact with the iron surface, they generate a passive iron phosphate layer. Wash primers must be quickly topcoated for maximum effectiveness and to prevent rust breakthrough.

13.3.2.2 Zinc-rich primers—These primers are organic or inorganic coatings with a high loading of zinc dust. When there is a rupture or discontinuity in the coating system, the zinc pigment particles protect the substrate by galvanic action. Because zinc reacts readily with both acids and strong alkalis, zinc-rich primers must be topcoated with chemically resistant coatings when used offshore because of exposure to alkaline drilling mud and acidic well-completion fluids. Zinc-rich primers are

⁽¹⁰⁾ Bureau of Mines, 2402 E. Street NW, Washington, DC 20241.

excellent preconstruction primers because of their abrasion and impact resistance and ability to protect the steel during long construction cycles. However, care must be taken to ensure that the zinc-primed surface is clean prior to topcoating. Fresh-water washing or power scrubbing may be required to remove contaminants.

13.3.2.3 Organic inhibitive primers—These materials may be solvent-based, chemically cured coatings, or thermoplastics, which form films by solvent evaporation. Chemically cured coatings generally require mixing of a second component for curing. Characteristically, these coatings include inhibiting pigments that must meet regulatory standards and limitations and be environmentally safe. On contact with moisture, the pigments generate either alkaline or ionic conditions that retard the corrosion of the base metal. Because these primers generally contain reactive pigments and are only part of a protective coating system, they must be protected with topcoats to perform as effective environmental barriers. Primers must conform to all applicable regulations regarding toxicity, safety, and environmental standards.

13.3.3 Topcoats—Primers used for offshore structures should be overcoated with intermediate and/or finish coats. These coatings function as barriers, retarding and restricting the permeation of water vapor, oxygen, and active chemical ions. Topcoats may also provide added impact resistance and solvent resistance, as well as an aesthetically pleasing finish. Generic characteristics of topcoats include the following:

13.3.3.1 Chemically Cured Coatings—These materials are usually epoxies, epoxy phenolics, polyesters, or some polyurethanes that are cured by mixing with a second component commonly called a “catalyst” or converter. These coatings, which are often applied in films exceeding 100 μm (4 mils) thickness per coat, have excellent chemical-resistant properties. Because these materials continue to cure on exposure, they become increasingly hard, brittle, and solvent-resistant with age. Therefore, recoating may require sweep blasting to achieve good mechanical bonding. With the exception of some polyurethanes, these coatings tend to chalk on exposure to ultraviolet light. These materials tend to be temperature- and moisture-sensitive during curing and require adequate temperatures and humidity control to cross-link and develop into chemically resistant films.

13.3.3.2 Solvent-Deposited or Thermoplastic-Type Coatings—These materials include vinyl acrylics, vinyls, or chlorinated rubbers. These coatings dry by the evaporation of solvents, which distinguishes them from epoxies, polyesters, and other chemically cured coatings. The change from a liquid to a solid state is not accompanied by any chemical change. This mode of drying permits

coating application at relative humidities of up to 90% and temperatures as low as 0°C (32°F). These coating films generally exhibit excellent resistance to environmental conditions. These solvent-soluble films simplify overcoating by providing solvent bonding between a refresher and previous coat. Principal disadvantages of these coating materials are limited temperature resistance (60 to 77°C [140 to 170°F]), reduced solvent resistance, and low solids-by-volume content. Because of the low solids-by-volume content, additional coats may be required to achieve the desired thickness. Recent technology indicates greater film and solids-by-volume capabilities may reduce the number of coats previously required. However, their chemical resistance may be impaired. Furthermore, regulations regarding volatile organic compounds (VOC) limitations may prohibit the application of the materials in some localities.

13.3.4 Thermal-sprayed aluminum

13.3.4.1 Thermal-sprayed aluminum (either flame or arc) applied to 200 μm (8 mils) and sealed with a silicone sealer has been used in atmospheric service for specific applications such as flare booms. Good surface preparation and cleanliness are essential. Ninety-nine percent or higher-purity aluminum or Al-5Mg is most commonly used with two or more spray passes used in the application. The sealer enhances service life and appearance. U.S. Military Specification MIL-STD-2138¹² offers guidelines for application and quality control.

13.3.4.2 Coating adhesion should exceed 7,000 kPa (1,000 psi) (see Paragraph 10.4.6.2).

13.4 Criteria for Coating Selection

13.4.1 Accelerated tests designed for coating selection include:

(a) Salt spray testing (4,000 h) in accordance with ASTM B 117.²²

(b) Weatherometer testing (2,000 h) in accordance with ASTM G 152,²³ ASTM G 153,²⁴ ASTM G 154,²⁵ or ASTM G 155.²⁶

(c) Humidity cabinet testing (4,000 h) in accordance with ASTM D 2247.²⁷

Some operators run combinations of the above tests on a rotating basis, such as 1,000 h in salt spray, 1,000 h in a weatherometer, followed by an additional 1,000 h in salt spray, and a final 1,000 h in a weatherometer.

13.4.2 Other coating properties that can be determined from laboratory tests and that may aid in evaluating materials are:

RP0176-2003

ASTM D 522²⁸

ASTM C 633¹³

ASTM D 968²⁹

ASTM D 3359³⁰

ASTM D 3363³¹

ASTM D 4214³²

Equivalent tests from organizations other than ASTM may be used.

13.4.3 The coating system ultimately selected depends on many environmental, application, and performance considerations, including the following:

13.4.3.1 The length of time primed steel is stored during construction periods and resistance to abrasion associated with handling and fabrication with a minimum of damage.

13.4.3.2 Coating systems that can be applied and maintained with conventional and readily available application equipment.

13.4.3.3 Cold temperatures and inclement weather restrictions for structures placed in northern latitudes.

13.4.3.4 Chemically cured coatings that have high impact resistance and resistance to spills of solvents and corrosive chemicals are often used on the deck areas of offshore structures because of anticipated exposure to weathering, abrasion associated with drilling operations, and spills of drilling mud, formation fluids, diesel fuels, lubricants, and well-completion compounds.

13.4.3.5 Offshore coatings are exposed to high-intensity ultraviolet light and should be resistant to heavy chalking and color fade.

13.4.3.6 Coating systems that are easily repaired and maintained are usually preferred.

13.4.3.7 Inorganic zinc-rich primers, when damaged and exposed in service, do not readily accept another coat of inorganic zinc-rich primer (IOZ), and are normally repaired with an organic zinc-rich coating or chemically cured, inhibited primer.

13.5 Storage, Handling, and Mixing of Materials

13.5.1 All materials used in the initial or maintenance coating of offshore structures should be furnished in the manufacturer's original, unopened container, clearly labeled to identify the contents. The materials should be stored in a manner that prevents exposure to

weather extremes, with 10 to 32°C (50 to 90°F) being optimum.

13.5.1.1 Thinners, diluents, or clean-up materials should comply with the coating manufacturer's recommendation, or if independently purchased, they should be of compositions approved by the coating manufacturer.

13.5.1.2 Single-supplier responsibility should be maintained by using primers, intermediates, and finish coatings from the same supplier.

13.5.1.3 All coating materials should be thoroughly agitated prior to application. If there is settling of the pigment, it should be redispersed with a power agitator to form a uniform mixture. For two-component materials, the catalyzed mixture also should be agitated with a power mixer. For heavily pigmented coating, such as zinc-rich primer, agitation should be continued during application to prevent settling.

13.5.1.4 Mixed coating solutions should be strained through a 250 to 600 µm (30 to 60 mesh) screen to remove any foreign materials or undispersed pigment particles.

13.5.1.5 When materials incorporating a catalyst or converter are mixed, the addition of converter beyond that recommended by the manufacturer has an adverse effect on the coating's application, curing, and performance characteristics.

13.5.1.6 Solvent can closures should be kept tight at all times to prevent the entrance of humid air, which can lead to condensation.

13.5.1.7 Manufacturer's shelf life recommendations for structure coating components should be followed.

13.6 Application Equipment

13.6.1 Most coatings are applied by spray. Conventional spray pressure pots shall be equipped with dual regulators and an air-driven agitator. All spray equipment must be equipped with fluid tips, needles, and air caps consistent with the coating manufacturer's recommendations. The air supply line to the pressure tank must be fitted with an efficient oil and moisture separator. For applications by airless spray, a hydraulic pump that achieves a minimum pressure-compounding ratio of 30:1 should be used. An atomizing tip consistent with the manufacturer's recommendation should be selected. The tip should provide the degree of atomization and optimum fan width consistent with the configuration of the structure to be coated.

13.6.2 Clean cans and strainers should be provided for mixing the coating materials.

13.6.3 An air source that can supply a minimum of 0.85 m³/min (30 cfm) at 690 kPa (100 psig) at the nozzle for spraying operation should be available.

13.7 Typical Coating Systems in Use

13.7.1 Table 3 illustrates coating systems commonly used in the atmospheric zone of offshore structures

and associated equipment. These systems are not presented as recommendations, nor does the order listed indicate preference or superiority of one system over another. The selection of a coating system should be based on the criteria outlined in Paragraph 13.4 and/or results from field experience and maintenance programs.

Table 3: Typical Coating Systems Used in the Atmospheric Zone^(A)

Coating System	Thickness	
	μm	mils
Inorganic zinc-rich self-cured primer	75	3
Epoxy tie-coat	50	2
High-build polyurethane	150 to 200	6 to 8
Epoxy intermediate and topcoat (2 coats)	250	10
Vinyl high-build intermediate coat	100 to 150	4 to 6
Vinyl topcoat (2 coats)	50	2
Epoxy intermediate coat	100 to 150	4 to 6
Vinyl acrylic or polyurethane topcoat	50	2
Co-polymer tie-coat	50	2
Vinyl high-build topcoat	150 to 250	6 to 10

^(A) The specified number of coats and the thickness may vary among operators and manufacturers

13.7.2 Maintenance coatings must be compatible with the original coating system.

13.7.3 The frequency and extent of recoating or touch-up work to be performed depends on many variables, including the following items:

- (a) Extent and location of corrosion damage on the structure,
- (b) Stress or loading of the affected structure members,
- (c) Danger of spills and leaks from production piping and vessels,
- (d) Cost of recoating work, including set-up charge,
- (e) Cost of deferred production and any equipment downtime during coating operations,
- (f) Safety of personnel, and
- (g) Appearance factors.

13.8 Coatings for Production Equipment and Piping located on Structures

13.8.1 For most equipment operating at ambient temperatures, many of the systems listed in Table 3 are in widespread use.

13.8.2 Some surfaces on heaters, compressors, or other equipment may have elevated temperatures. If coatings are needed on these surfaces, special high-temperature coatings are available. Other processes, such as metalizing, porcelainizing, or using ceramic coatings, may also be considered.

13.8.3 For intricate shapes such as manifolds and christmas trees, care must be taken to avoid applying an excessively thick coating (see Paragraph 13.9.5).

13.9 Special Problems in Offshore Coating Programs

13.9.1 Thorough planning is necessary for applying coatings offshore. The problems of logistics, accessibility, scheduling, housing, and storage are more critical and far more costly than when applying coatings onshore.

13.9.2 The structure to be coated should be surveyed by representatives of the owner, supplier, and the contractor to consider the following aspects of the structure:

- (a) Accurate area measurements,
- (b) Condition of steel,
- (c) Protection of production equipment required,

(d) Type and amount of rigging scaffolds and safety equipment required,

(e) Deck space and housing,

(f) Availability of transportation for workers, equipment, material, and supplies,

(g) Excess equipment on structures that may require moving, and

(h) Appropriateness of specified coating systems based on the exposure and logistics of the structure.

13.9.3 In scheduling and coordinating structure operation, the coating work should be given special consideration. Company personnel must be informed of the coating work to prevent salt-water washdowns and spills of oil or mud chemicals on blasted or primed surfaces. Workovers, drilling, or construction can seriously hinder or delay the coating work.

13.9.4 Company personnel and inspectors must be familiar with the problems and requirements of surface preparation and application of the coating materials.

13.9.5 In applying coating to intricate shapes or in pipe-congested areas, it is difficult to maintain thin films. Coatings such as inorganic zinc-rich primers, which are sensitive to excessive thickness and mud-

crack and spall at a thickness of about 100 μm (4 mils) or more, must be avoided unless special care is exercised during application.

13.10 Galvanizing

13.10.1 Hot-dip galvanizing is an effective method for protecting complex steel shapes that would be costly and difficult to coat by conventional means. Such shapes as grating, handrails, stairs, meter houses, equipment skids, and others may be protected by galvanizing.

13.10.2 Galvanizing, like other zinc coatings, is subject to attack by acid and alkaline conditions, and should not be exposed to cement, drilling mud, or well acid.

13.10.3 Because galvanized coatings sacrifice themselves galvanically when exposed in the splash zone or when immersed, causing rapid breakdown or failure, other materials or overcoating should be used instead.

13.10.4 Galvanized metal can be overcoated by the use of suitable primers and topcoats for better chemical and salt-water exposure.

13.10.5 All galvanizing shall be applied in accordance with ASTM A 123³³ and A 153.³⁴

Section 14: Coatings Inspection

14.1 Introduction

14.1.1 This section provides inspection procedures to verify compliance with the governing coating specifications.

14.1.2 The inspection tools suggested for use by the inspectors are needed to provide acceptable results. Judgment based on broad experience, however, is the best inspection tool available.

14.1.3 A pre-job conference should be held to stipulate the responsibilities and relationship of the owner, inspector, applicator, and coatings supplier.

14.2 Job Orientation

14.2.1 Inspectors should thoroughly familiarize themselves with the particular job to be done. Careful notes should be made initially so that confusion is eliminated later. Acknowledgement of receipt of project specification, and understanding of same, should be made.

14.2.2 Inspectors should acquaint themselves with the materials to be used on the job.

14.2.2.1 The specification should state abrasive requirements and anchor pattern according to standards on which a mutual agreement has been reached.

14.2.2.2 All coating materials should be checked at the job site for conformance to specifications. Prior to the initiation of the job, the inspector should be provided the applicable product technical and material safety information; such information shall be made readily available by the coatings supplier. Incompatibilities should be reported prior to initiation of the job.

14.2.3 The inspector should make an initial inspection of all equipment on the job site to ensure and document that it meets the job requirements.

14.2.3.1 Special attention should be paid to abrasive-blasting equipment. The inspector should verify and enforce the specifications for abrasive-blast equipment to ensure that the compressors are sized properly for the number of nozzles and hoses, and that gaskets and nozzles are properly sized and in good condition. Air quality should be checked for cleanliness and dryness (see Para-

graph 12.5.1.3). Documentation of verifications should be made.

14.2.3.2 The inspector should routinely inspect painting equipment to see that it is in good condition and meets manufacturer's specifications for the materials to be applied. Documentation of verifications should be made.

14.2.3.3 Rigging and special scaffolding equipment should be checked for safety and adequacy for the job and compliance with the owner's and applicable regulatory requirements.

14.2.3.4 The inspector should inspect all surfaces blasted to ensure that they meet specifications prior to any coating application.

14.3 Coating Application

14.3.1 The inspector should not allow coating application when the steel temperature is within 3°C (5°F) of the dew point.

14.3.2 The inspector should check the application equipment to ensure that proper pressures are being used for the materials specified.

14.3.3 The inspector should check each applicator to ensure that proper techniques are being used. Unsafe practices should be reported.

14.3.4 The inspector should ensure that materials sequence specifications are being followed.

14.3.4.1 The dry film thickness (DFT) of each coat should be checked to ensure that thickness specifications are met.

14.3.4.2 The cure or drying time should be checked to ensure that specifications are followed.

14.3.5 The final surface can be checked for holidays on nonconducting films.

14.3.6 The inspector should approve or disapprove all surfaces prior to beginning the next coating operation. Surfaces not meeting specifications should be redone.

14.3.7 The inspector should ensure that all surfaces to be coated are free of oil, grease, salt deposits, and moisture.

14.4 Inspection Equipment

14.4.1 The nozzle orifice gauge is required for measuring wear on abrasive-blast nozzles.

14.4.2 The nozzle pressure gauge is required to measure actual pressure at the nozzle.

14.4.3 A surface profile comparator can be used to determine surface profile or anchor pattern. Replica tapes as described in NACE Standard RP0287³⁵ can also be used to measure the anchor pattern.

14.4.4 A set of NACE surface preparation standards for comparing surface preparation is recommended (see Paragraph 12.3).

14.4.5 A humidity gauge or sling psychrometer should be used to measure humidity and temperature.

14.4.6 A wet-film thickness gauge should be used.

14.4.7 Dry-film thickness (DFT) should be measured with a nondestructive magnetic-type dry-film thickness gauge.

14.4.8 A wet sponge-type holiday detector can be used on nonconducting coatings for detecting holidays. A high-voltage holiday detector is an alternative for high-build coatings (DFT >1 mm [40 mils]).

14.4.9 A pocket knife or Tooke gauge may be used to check interfilm adhesion and hardness and to determine whether all coats of a multicoat system were applied. This is a destructive test and should be employed as a last resort.

14.4.10 A variable-width cross-hatch knife blade guide can be useful for conducting the adhesion test described in Paragraph 14.4.9.

14.4.11 Other inspection equipment might include mirrors, solvents, sample containers, adhesive tape, thermometers, and a surface roughness gauge.

14.5 Job Evaluation and Records

14.5.1 The inspector should keep a daily record that includes all phases of the work.

14.5.1.1 The notes should record the number of men working, equipment used, hours worked, and weather conditions.

14.5.1.2 A record of all materials used during any day should be made. This should include abrasives, coatings, solvents, and other materials.

14.5.1.3 Appropriate records indicating the degree of compliance to the coating specification should be completed by the inspector.

14.5.1.4 Records of type and location of coating repairs should be kept.

14.5.2 The inspector should note job progress.

14.5.2.1 The inspector should note job progress of each individual in m² (ft²) per day.

14.5.2.2 The inspector should note total job progress of the entire crew per day and record as total m² (ft²) per day.

14.5.3 The job may be evaluated using data from Par-

agraphs 14.5.1 through 14.5.2.2 as measures of crew efficiency and cost per m² (ft²).

14.5.4 Complete records should be kept so that coating systems can be evaluated on the basis of cost per m² (ft²) per year.

Section 15: Corrosion Control Records

15.1 Introduction

15.1.1 This section describes a system of corrosion control records for documenting data pertinent to the design, installation, operation, maintenance, and effectiveness of the CP and coating systems.

15.1.2 Included in this section is an exhaustive listing of possible records. Each operator should decide on the records that are necessary for control of corrosion on the structure.

15.1.3 Information regarding the location of anodes, electrical leads, and rectifiers can be conveniently recorded on a drawing of the structure being protected. More of the potential survey data and results of maintenance inspections can be maintained in tabular form and kept up-to-date with periodic entries.

15.1.4 As-built drawings should reflect any changes from design specifications, particularly deviation in setting depth, which would alter the interval covered by the splash zone. Deviation in setting depth may occur through errors in water depth estimate (initial survey) or through settlement of the structure (possible over field life).

15.2 CP Systems

15.2.1 Galvanic (sacrificial) anode system—The following should be recorded:

15.2.1.1 Design criteria used: design life, assumed anode output and consumption rate, and current density requirements.

15.2.1.2 Number, size, composition, and (if known) the manufacturer, cost, and supplier of the anodes.

15.2.1.3 Location of each anode, the method of attachment, and date of installation. If anodes are installed during structure construction, the date of actual setting of the structure offshore should be recorded.

15.2.1.4 Number and location of anodes if checked either during construction or after setting on location, with all discrepancies noted.

15.2.2 Impressed current system—The following should be recorded:

15.2.2.1 Design criteria used (see Paragraph 15.2.1.1).

15.2.2.2 Number, size, composition, and (if known) the cost, manufacturer, and supplier of the anodes.

15.2.2.3 Location of each anode, method of attachment, and date of installation.

15.2.2.4 Specifications of the direct-current source.

15.2.2.5 Composition and location of any dielectric shielding used.

15.2.2.6 Current and voltage output of each rectifier as called for in Paragraphs 9.3 and 9.5, noting any adjustments made.

15.2.3 Combination system

15.2.3.1 A combination system is one containing galvanic (sacrificial) anodes in addition to an impressed current system.

15.2.3.2 Records for a combination system must include complete information for each of the component systems.

15.2.4 Structure potential measurements

15.2.4.1 Each time the potential of the structure is measured, the type of reference cell and the measuring technique (diver-held, guided, permanent, or freely suspended) used should be recorded.

15.2.4.2 The structure potential should be recorded initially and at the time intervals specified in Paragraph 9.4.

15.2.5 Operation and inspection—The following should be recorded:

15.2.5.1 Results of underwater inspection of the anode system, noting all discrepancies such as missing anodes.

15.2.5.2 Location, size, and type of corrosion damage found during any underwater inspection, and location and general description of trash metal located on and around the base of the structure.

15.2.5.3 Size, composition, location, number, method of attachment, cost, supplier, and date of installation of all replacement anodes.

15.2.5.4 Any maintenance performed on the rectifier.

15.2.5.5 Downtime of the impressed current system, whenever possible.

15.2.5.6 Any enlargement of the structure or addition of pipelines and flowlines. Any deviation in setting depth (see Paragraph 15.1.4).

15.3 Coating and Cladding Systems

15.3.1 This section pertains to the coatings used in atmospheric and submerged zones and the special coatings and claddings, both metallic and nonmetallic, used in the splash zone.

15.3.2 When wear plates are specified for the splash zone, the anticipated corrosion rate assumed in the design calculations should be recorded.

15.3.3 Initial installation—The following should be recorded:

15.3.3.1 Surface preparation, primer, intermediate, and topcoats used, including the quality of

surface preparation, the DFT of each coat, and the number of coats.

15.3.3.2 Coating manufacturer(s), applicator, and date of application.

15.3.3.3 Inspection procedure and the results of any spot tests for film thickness and holidays.

15.3.3.4 Cost of surface preparation, coating material, and coating application.

15.3.4 Inspection

15.3.4.1 Coating and cladding systems should be inspected on a regular basis.

15.3.4.2 Location, type, and amount of deterioration found should be recorded during each inspection.

15.3.5 Maintenance—The following should be recorded:

15.3.5.1 Date of each touch-up and recoating job and the reason for the job, such as post-erection, post-drilling, routine maintenance, etc.

15.3.5.2 Total area recoated, the surface preparation and coating system used, and the inspection procedure.

15.3.5.3 Name of the coating contractor, labor materials, and equipment used, and the total cost of the job.

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Appendix A: Typical Design Parameters for Offshore Petroleum Production

Structures in Selected Oil Provinces

The principal factor governing the minimum design current density at which polarization necessary for complete CP can be achieved in the open sea is the availability of corrosive (depolarizing) agents, principally oxygen, at the submerged structure surfaces. Lowering the water temperature increases both the water resistivity and oxygen solubility. Water turbulence, along with natural lateral flow, also maximizes the rate at which oxygen reaches the structure surfaces. Cook Inlet waters represent an environmental extreme; most of the above negative factors are present, in addition to scouring (mechanical depolarization) by suspended glacial silt in the swiftly flowing water.

The formation of a calcareous deposit also affects the current requirement by reducing the ability of oxygen to reach the metal surface. The calcareous deposit precipitates from seawater because of the alkaline shift in pH that results from the polarization of the metal surface. Because the beneficial qualities of the calcareous deposit are reduced by decreasing water temperature and lower current densities, a relatively high initial current provision for CP can reduce the long-term current demand to maintain protection.

Laboratory and field tests have shown that rapid polarization of a steel cathode upon immersion to potentials of -0.9 to -1.0 V (Ag/AgCl [sw]) generates a more protective calcareous deposit than is achieved by slower polarization. High

current densities are required to achieve these results, but current demand decreases (by as much as a factor of 10) quickly as the protective calcareous deposit is formed. At the launch of a structure the potential difference between the sacrificial anode system and the unpolarized steel may be around 0.45 V, which enables the sacrificial system to generate a very high current density on the cathode. After polarization, this potential difference decreases to 0.25 V or less with an accompanying decrease in current density.

This polarization process normally results in a linear relationship between steel potential and current density, the slope of the line being equal to the overall circuit resistance of the CP system, or the design slope. For any given location, galvanic anode designs with similar design slope values result in similar long-term current densities. The relationship between design slope and maintenance current density can be established by on-site experiments or by review of experience at that location.

Current density is strongly dependent on water temperature. For deep-water structures different design values should be used for different temperature zones. To optimize the design the structure should be spilt up into separate zones

over which the temperature does not vary by more than 5°C (9°F). The depth average temperature of each interval should be used to assess the required current densities.³⁶ The same approach can apply to resistivity assessment.

Table A1 presents a general guide to the design of CP systems in eleven major offshore petroleum producing areas. These data may be used as a starting point for investigation prior to selection of final design parameters for a specific application. Table A1 also presents equivalent design values for the same producing areas.

Figure A1 represents the temperature curves based on current density.

Table A1: Design Criteria For Cathodic Protection Systems

Production Area	Water Resistivity ^(B) (ohm-cm)	Water Temp. (°C)	Environmental Factors ^(A)		Typical Design Current Density ^(C) mA/m ² (mA/ft ²)			Typical Design Slope ohm-m ² (ohm-ft ²)
			Turbulence Factor (Wave Action)	Lateral Water Flow				
					Initial ^(E)	Mean ^(F)	Final ^(G)	
Gulf of Mexico	20	22	Moderate	Moderate	110 (10)	55 (5)	75 (7)	4.1 (44)
U.S. West Coast	24	15	Moderate	Moderate	150 (14)	90 (8)	100 (9)	3.0 (32)
Cook Inlet	50	2	Low	High	430 (40)	380 (35)	380 (35)	1.0 (11)
Northern North Sea ^(D)	26 to 33	0 to 12	High	Moderate	180 (17)	90 (8)	120 (11)	2.5 (27)
Southern North Sea ^(D)	26 to 33	0 to 12	High	Moderate	150 (14)	90 (8)	100 (9)	3.0 (32)
Arabian Gulf	15	30	Moderate	Low	130 (12)	65 (6)	90 (8)	3.5 (37)
Australia	23 to 30	12 to 18	High	Moderate	130 (12)	90 (8)	90 (8)	3.5 (37)
Brazil	20	15 to 20	Moderate	High	180 (17)	65 (6)	90 (8)	2.5 (27)
West Africa	20 to 30	5 to 21	Low	Low	130 (12)	65 (6)	90 (8)	3.5 (37)
Indonesia	19	24	Moderate	Moderate	110 (10)	55 (5)	75 (7)	4.1 (44)
South China Sea	18	30	Low	Low	100 (9)	35 (3)	35 (3)	

**Resistivities (ohm-cm)
Temperature (°C [°F])**

Chlorinity (ppt)	0 (32)	5 (41)	10 (50)	15 (59)	20 (68)	25 (77)
19	35.1	30.4	26.7	23.7	21.3	19.2
20	33.5	29.0	25.5	22.7	20.3	18.3

^(A) Typical values and ratings based on average conditions, remote from river discharge.

^(B) Water resistivities are a function of both chlorinity and temperature. In the Corrosion Handbook³⁷ by H.H. Uhlig the following resistivities are given for chlorinities of 19 and 20 parts per thousand (ppt).

^(C) In ordinary seawater, a current density less than the design value suffices to hold the structure at protective potential once polarization has been accomplished and calcareous coatings are built up by the design current density. CAUTION: Depolarization can result from storm action.

^(D) Conditions in the North Sea can vary greatly from the northern to the southern area, from winter to summer, and during storm periods.

^(E) Initial current densities are calculated using Ohm's Law and a resistance equation such as Dwight's or Crennell's (McCoy's) equation with the original dimensions of the anode. An example of this calculation is given in Appendix D, which uses an assumed cathode potential of -0.80 V (Ag/AgCl [sw]).

^(F) Mean current densities are used to calculate the total weight of anodes required to maintain the protective current to the structure over the design life. Examples of these calculations are given in Appendixes D and E.

^(G) Final current densities are calculated in a manner similar to the initial current density, except that the depleted anode dimensions are used. An example of this calculation is given in Appendix D.

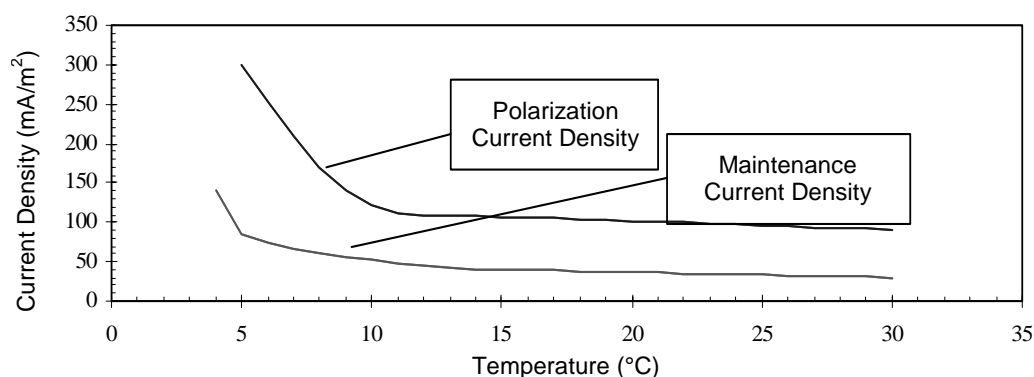


Figure A1: Current Density/Temperature Curves

Appendix B: Energy Capabilities and Consumption Rates of Various Commercial Galvanic Anodes Available for Cathodic Protection of Offshore Structures

The energy capability of a given galvanic anode material is usually expressed in terms of ampere-hours per kg (lb) of material. This figure, when divided into the number of hours per year (8,760), gives the anode consumption rate in kg (lb) per ampere-year, a more useful form of energy rating to the design engineer.

The energy capability of any galvanic anode material selected for use in offshore CP design should be previously established through controlled laboratory and field tests at an anode current density normally expected in field applications, i.e., approximately 2.2 to 7.5 A/m² (200 to 700 mA/ft²) of anode surface. Table B1 lists the established energy capabilities of some of the more commonly used galvanic anode materials at anode loadings of 2.2 to 7.5 A/m² (200 to 700 mA/ft²). The differences shown for any one material are attributed to variations in composition and/or heat treat-

ment offered by the various manufacturers. Table B1 also lists the corresponding anode consumption rates, calculated as stated above. Therefore, it is prudent in design of galvanic CP systems to consider that anode capacity may be less than is predicted from short-term testing.

Segregation of some minor alloys and/or impurities during cooling can alter the galvanic properties of the anode material. Any potential segregation is more pronounced on the interior portions of larger anodes because of slower cooling after casting.

Any anode material must be capable of a sufficient driving voltage to provide the necessary design current output. A check for proper driving voltage of an anode can be made by measuring the closed-circuit potential of the anode, using a suitable reference cell.

Table B1: Energy Capabilities and Consumption Rates of Galvanic Anode Materials in Seawater

Galvanic Anode Material	Energy Capability ^(A) A-h/kg (A-h/lb)	Consumption Rate Kg/A-yr (lb/A-yr)	Anode to Water ^(B) Closed Circuit Potentials, Negative Volts (Ag/AgCl[sw])
Aluminum-zinc-indium	2,290 to 2,600 (1,040 to 1,180)	3.8 to 3.4 (8.4 to 7.4)	1.05 to 1.10
Aluminum-zinc-mercury	2,760 to 2,840 (1,250 to 1,290)	3.2 to 3.1 (7.0 to 6.8)	1.0 to 1.05
Aluminum-zinc-tin	930 to 2,600 (420 to 1,180)	9.5 to 3.4 (20.8 to 7.4)	1.0 to 1.05
Zinc (MIL-A-18001) ⁸	770 to 820 (350 to 370)	11.2 to 10.7 (25.0 to 23.7)	1.0 to 1.05
Magnesium (H-1 alloy)	1,100 (500)	8.0 (17.5)	1.4 to 1.6

^(A) The above data show ranges that are taken from field tests at Key West, Florida, by Naval Research Laboratory, Washington, DC,³⁸ and from manufacturers' long-term field tests. Modification to these numbers will be made only by recommendation from NACE International STG 30 on Oil and Gas Production—Cathodic Protection.

^(B) Measured potentials can vary because of temperature and salinity differences.

Appendix C

Consumption Rates in Seawater of Various Commercial Types of Impressed Current Anodes Available for Cathodic Protection of Offshore Structures

Impressed current anodes, unlike galvanic anodes, can be driven over a wide range of anode current densities, depending on the designer's preferences and the demands of a particular application. Because anode current loadings have a definite bearing on consumption rates, any meaningful listing of consumption rates for various anode materials must necessarily include the approximate anode current density at which such rates have been established.

Table C1 lists consumption rates of various impressed current anode materials used for CP systems on offshore structures. If titanium is used as the substrate for a platinum-type anode, anode/electrolyte voltage must be limited to about 8 V. For niobium substrates, laboratory data indicate that voltages as high as 100 V are satisfactory; however, field experience shows that 50 V is a more reliable and practical limit.

Table C1: Consumption Rates of Impressed Current Anode Materials

Impressed Current Anode Material	Typical Anode Current Density in Saltwater Service A/m ² (A/ft ²)	Nominal Consumption Rate g/A-yr (lb/A-yr)
Pb-6%Sb-1%Ag	160 to 220 (15 to 20)	14 to 90 (0.03 to 0.2 ^(A))
Pb-6%Sb-2%Ag	160 to 220 (15 to 20)	14 to 27 (0.03 to 0.06 ^(B))
Platinum (on Titanium, Niobium, or Tantalum substrate or mixed metal oxide)	540 to 3,200 (50 to 300)	3.6 to 7.3 (0.008 to 0.016 ^(B))
Graphite	10 to 40 (1 to 4)	230 to 450 (0.5 to 1.0)
Fe-14.5%Si-4.5%Cr	10 to 40 (1 to 4)	230 to 450 (0.5 to 1.0)

^(A) Very high consumption rates of Pb-Ag anodes have been experienced at depths below 30 m (100 ft).

^(B) This figure can increase when current density is extremely high and/or in low-salinity waters.

Appendix D: Typical Method for Calculation of Galvanic Anode Current Output Using Initial, Maintenance, and Final Current Densities

This method has been commonly employed in the past for CP design, so practitioners tend to be familiar with it. The disadvantage is that it is based on an algorithm rather than being first principles-based and can lead to unnecessary over-design compared to the slope parameter method (see Appendix E). The over-design can be minimized if a range of anode sizes is considered, and the size selected on the one that gives the lowest installed cost.³⁶ From a modification of Dwight's equation,³⁹ the resistance of a cylindrically shaped anode to the electrolyte in which it is placed is equal to the product of the specific resistivity of the electrolyte and certain factors relating to the shape of the anode, as given in Equation (D1):

$$R = \rho \frac{K}{L} \left[\ln \left(\frac{4L}{r} \right) \right] - 1 \quad (D1)$$

where:

R = anode-to-electrolyte resistance in ohms

ρ = resistivity of the electrolyte in ohm-cm. (See Table A1)

K = 0.500/ π or 0.159 if L and r units are in cm or 0.0627 if L and r units are in inches

L = length of anode in centimeters

r = radius of anode in centimeters (for other than cylindrical shapes, $r = C/2\pi$, where C = cross-section perimeter).

Thus, for a 25 x 25 cm (10 x 10 in.) cross-section, C = 100 cm (40 in.), and r = 15.9 cm (6.27 in.).

To determine the current output from an anode, use Ohm's Law: $I = E/R$.

For a typical calculation for an anode in the Gulf of Mexico, the number of anodes required for protection must satisfy three different calculations. There must be enough anodes to polarize the structure initially (initial current density from Table A1), to produce the appropriate number of amps of current over the design life of the structure (mean current requirement), and to produce enough current to maintain protection at the end of the design life (final current require-

ment). For this exercise, we are given the following information:

Structure surface area = 9,300 m² (100,000 ft²)

Design life = 20 years

$\rho = 20$ ohm-cm (from Table A1).

Based on this information, we select an anode with the following characteristics:

Material: aluminum-zinc-mercury alloy

$E = 0.25$ V driving force between an aluminum or zinc anode of -1.50 V (Ag/AgCl [sw] reference).

$L = 244$ -cm (96-in.) anode length,

$r = 13.7$ -cm (5.40-in.) anode radius initially for a 22- x 22-cm (8.5- x 8.5-in.) anode on a 10-cm (4-in.) core,

$Wt = 330$ -kg (725-lb) weight per anode,

$CC = 2,750$ A-hr/kg (1,250 A-hr/lb) for current capacity for Al-Zn-Hg alloy anodes from Table B1 or anode supplier's specifications,

$r_{core} = 5.7$ cm (2.25 in.), which is one-half the OD of an 11-cm (4-in.) Sch. 80 pipe.

Therefore, the initial current output per anode is as shown in Equation (D2):

$$I = \frac{E}{R} = \frac{0.25V}{20 \frac{0.159}{244} \left[\ln \left(\frac{4 \times 244 \text{ cm}}{13.7 \text{ cm}} \right) - 1 \right]} = \frac{0.25V}{0.0426 \text{ ohm}} = 5.86A \quad (D2)$$

The number of anodes required to protect a structure with 9,300 m² (100,000 ft²) of exposed surface area is as shown in Equation (D3):

$$N = \frac{\text{Initial Current Density (110 mA/m}^2\text{)} \times \text{Surface Area (9,300 m}^2\text{)}}{\text{Amps output per anode (5.86) } \times 1,000 \text{ mA/A}} = 175 \text{ anodes} \quad (D3)$$

The initial current density (110 mA/m²) is obtained from Table A1.

In order to meet the second current density requirement for the structure, which determines the number of kg (lb) of anode material required to protect the structure over the 20-year design life, use Equation (D4):

$$N = \frac{\text{Mean Current Density (55 mA/m}^2\text{)} \times \text{Surface Area (9,300 m}^2\text{)} \times \text{Life (20 yr)} \times 8.760 \text{ (hr/yr)}}{(2,750 \text{ A hr/kg} \times 330 \text{ kg/anode} \times 1,000 \text{ mA/A})} = 99 \text{ anodes} \quad (D4)$$

The mean current density (55 mA/m²) is obtained from Table A1.

Lastly, the number of anodes to provide the final current requirement is calculated in a manner similar to the initial current requirement, except that the expended dimensions of the anode are used to represent the anode at the end of its life (see Equation (D5)).

$$r_{\text{expended}} = r_{\text{initial}} - (r_{\text{initial}} - r_{\text{core}}) \times 0.9 = 13.7 - [(13.7 - 5.7)(0.9)] = 6.5 \text{ cm} \quad (D5)$$

where 0.9 is the anode utilization factor for a standoff anode. Assume no change in anode length.

The final current output per anode is shown in Equation (D6):

$$I = \frac{E}{R} = \frac{0.25V}{20 \frac{0.159}{244} \ln \frac{4 \times 244 \text{ cm}}{6.5 \text{ cm}}} = \frac{0.25V}{0.0523 \text{ ohm}} = 4.78 \text{ A} \quad (D6)$$

The number of anodes required to protect a structure with 9,300 m² (100,000 ft²) of exposed surface area is as shown in Equation (D7):

$$N = \frac{\text{Final Current Density (75 mA/m}^2\text{)} \times \text{Surface Area (9,300 m}^2\text{)}}{\text{Amps output per anode (4.78) } \times 1,000 \text{ mA/A}} = 146 \text{ anodes} \quad (D7)$$

The final current density (75 mA/m²) is obtained from Table A1.

The initial current calculation required 175 anodes, the mean current density requirement required 99 anodes, and the final current calculation required 146 anodes. For this application the proper number of anodes to use would be 175 anodes. However, the difference between this value and the calculated mean current requirement of 99 anodes is significant. Another anode shape that provides less variation between the three requirement values is often more economical to install.

Dwight's equation is valid when $4L/r \geq 16$; for anodes when $4L/r < 16$ or for anodes that do not approximate cylindrical shapes, equations such as Crennell's (McCoy's) (see Equation [D9]) or other versions of Dwight's may better predict the actual current output of the anodes. Theoretically, for a deep sea submerged cylindrical anode, a more nearly correct equation would be as shown in Equation (D8):

$$R = \rho \frac{K}{L} \left[\ln \left(\frac{2L}{r} \right) - 1 \right] \quad (D8)$$

However, the first version is more widely used in CP practice.

Notes:

(a) For practical designs and to ensure adequate current to protect the structure during the life of the anode, the length (L) and radius (r) should be selected to show the condition of the anode when it is nearly consumed. For an elongated anode, the change in length may be ignored.

(b) If the structure potential rises above the minimum protection potential of -0.80 volt (Ag/AgCl [sw]), E becomes less than 0.25 V. This decreases anode current output and increases anode life.

(c) The anode net weight must be sufficient to provide the calculated current for the design life of the system, in accordance with the actual consumption rate of the anode material selected (see Appendix B and Table B1).

(d) Crennell's (McCoy's) formula is shown in Equation (D9)⁴⁰:

$$R = \frac{0.315\rho}{\sqrt{A}} \quad (D9)$$

where:

R = resistance in ohms
 ρ = resistivity of water in ohm-cm
 A = area of exposed anode in cm²

Appendix E: Typical Method for Calculation of Galvanic Anode Current Output Using Design Slope and Maintenance Current Density

This method is proposed as an alternative to calculation of the initial, mean, and final current densities (Appendix D). It affords the advantage of being first principles based such that undisclosed over-design, as may be inherent to the preceding method, may be avoided. This CP system design for the seawater-exposed sections of an uncoated structure using the design slope follows these steps⁴¹:

1. Determine the required design life for the structure, T.
2. Based on the anode material to be used and the application environment, select a value for the anode consumption rate, k (Note: a different symbol for anode consumption rate is used elsewhere).
3. Specify the water resistivity, ρ. For large structures that span zones of varying resistivity, separate designs may be executed for different regions of the structure.
4. Based on prior experience or on experimental data at the site of interest, select values for the design slope, S, and for the maintenance current density, i_m , which results from that design slope. Again, separate designs may be executed for different regions of the structure.

5. Determine the value of the right-hand side of Equation (E1). This value then describes the anode size and shape alternatives that may be used to achieve the selected design, as dictated by the left-hand side.

$$R_a w = i_m T k S \quad (E1)$$

where:

R_a = resistance of single anode to remote seawater (for example, Equation [D1]) in ohms
 w = weight of a single anode in kg
 i_m = maintenance current density in A/m²
 T = design life in years
 k = anode consumption rate in kg/A-yr
 S = design slope in ohm-m² (many or all of these terms are defined elsewhere)

6. Iteratively determine a suitable anode for the application:

(a) Select a candidate anode, and from its dimensions calculate its resistance, R_a , and its mass, w.

(b) Check whether for this anode, the left-hand side of Equation (E1) is equal to the right-hand side.

(c) If there is no match, two options exist. First the anode can be modified and steps 6a and 6b repeated to optimize the anode to meet the design criteria. (Although an infinite number of anodes that will satisfy Equation (E1) can be designed, there is a smaller subset that is practical to manufacture and install.) Alternatively, the selected anode may be accepted, and Equation (E1) may be rearranged, as shown in Equation (E2), to determine the actual design life that will result.

$$T = \frac{R_a w}{i_m k S} \quad (E2)$$

7. Once the anode has been sized, Equation (E3) can be used to calculate the surface area that each anode will protect, A_1 :

$$A_1 = \frac{S}{R_a} \quad (E3)$$

where:

A_1 = area protected per anode in m^2

8. Determine the total surface area for the structure or zone to be protected, A_{total} , and divide by the area protected by each anode to determine the number of anodes needed, as shown in Equation (E4).

$$N = \frac{A_{total}}{A_1} \quad (E4)$$

where:

N = total number of anodes

9. Determine whether the design slope based on final conditions (90% anode consumption) is acceptable but using the value of R_a for an expended anode. R_a of an expended anode can be calculated using the same procedure described to determine the current output of an expended anode in Equations D5 and D6. The long-term potential of the anode might be different from the value exhibited during the polarization process, so that the design line may shift up or down on the polarization graph.

If a large number of designs will be done for structures in similar conditions, steps 1 through 7 and 9 of this procedure may need to be followed only once. A standard anode that will protect a certain cathode area, A_1 , on each structure, is thereby defined.

If a design requires that different sizes and shapes of anodes be used because of complex structure geometry, then each anode type should be independently determined to satisfy the design equation in step 6 above. The area protected by each anode type is different.

Standard Recommended Practice

Impressed Current Cathodic Protection of Internal Submerged Surfaces of Carbon Steel Water Storage Tanks

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Approved 2001-10-22
Approved November 1988
NACE International
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ISBN 1-57590-138-2
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Foreword

The purpose of this NACE standard is to present the recommended practices for providing impressed current cathodic protection (CP) to the normally submerged steel surfaces inside water storage tanks. It contains recommendations for the design and installation of these cathodic protection systems and methods for determining the effectiveness of these systems. Recommendations for the operation and maintenance of both automatic and manual systems are also provided. This standard is applicable to relatively large water storage tanks used in municipal water supply and fire protection, including elevated and on-grade tanks. Although the general principles outlined in this standard are applicable to all such tanks, the impressed current cathodic protection system described in this standard may not be practical for smaller tanks. This standard is intended for use by engineers, water utilities, tank erectors and other contractors, and owner operators of steel water storage tanks.

This standard was originally prepared in 1988 by Task Group T-7L-1, a component of Unit Committee T-7L on Cathodic Protection. The task group was composed of corrosion engineers and others experienced in the design, installation, and maintenance of impressed current cathodic protection systems for water storage tanks. It was reaffirmed by T-7L in 1990, 1995, and revised in 2001 by Task Group 167 (formerly T-7L-14). Task Group 167 is administered by Specific Technology Group (STG) 05 on Cathodic/Anodic Protection. It is issued by NACE International under the auspices of STG 05.

In NACE standards, the terms *shall*, *must*, *should*, and *may* are used in accordance with the definitions of these terms in the *NACE Publications Style Manual*, 4th ed., Paragraph 7.4.1.9. *Shall* and *must* are used to state mandatory requirements. The term *should* is used to state something good and is recommended but is not mandatory. The term *may* is used to state something considered optional.

**NACE International
Standard
Recommended Practice**

**Impressed Current Cathodic Protection of Internal Submerged
Surfaces of Steel Water Storage Tanks**

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Section 1: General

1.1 This standard presents recommended practices for applying impressed current cathodic protection to the internal submerged surfaces of steel tanks used for the storage of natural waters. These tanks may be provided with an interior barrier coating. It is not intended for use with metallic coatings or linings, such as zinc or aluminum.

1.2 It is recognized that galvanic anode systems can, at times, be used for cathodic protection of the internal surfaces of water storage tanks; however, this standard addresses only impressed current systems.

NOTE: Information regarding galvanic cathodic protection of water storage tanks may be found in RP0196, "Galvanic Anode Cathodic Protection of Internal Submerged Surfaces of Steel Water Storage Tanks."¹

1.3 Natural waters, as used in this standard, include both potable and nonpotable fresh waters associated with water supply systems and fire protection.

1.4 The ground level and elevated storage tanks considered in this standard are of welded, bolted, or riveted steel construction and include many shapes and sizes.

1.5 Cathodic protection, as described in this standard, may be used alone to control corrosion of submerged steel surfaces or used as a complement to the protection afforded by protective coatings. Cathodic protection cannot protect surfaces that are not submerged. These surfaces must be protected by coatings alone. Cathodic protection does not reverse structural damage already caused by corrosion.

1.6 Cathodic protection may be installed to control corrosion in both newly constructed and existing tanks.

When cathodic protection is used on existing tanks, it is not necessary to prepare the surfaces to be protected; however, it may be necessary to drain the tank during installation.

1.7 It is recognized that the tanks under consideration are often associated with potable water and fire protection systems, which may be subject to public health and safety regulations. This standard should not infringe upon those regulations. Proper disinfection of the tanks may be required after installation. Any applicable regulations such as those from the U.S. Environmental Protection Agency (EPA)⁽¹⁾ and ANSI⁽²⁾/NSF⁽³⁾ -612 should be checked. In the United States, all materials in contact with potable water or exposed to the interior of potable water tanks must be classified in accordance with ANSI/NSF-61.

1.8 The provisions of this standard should be applied under the direction of a competent corrosion engineer. The term "corrosion engineer," as used in this standard, refers to a person who by reason of knowledge of the physical sciences and the principles of engineering and mathematics, as acquired by professional education and related practical experience, is qualified to practice corrosion control and cathodic protection for water storage tanks. Such persons may be registered professional engineers or persons certified by NACE International as Cathodic Protection or Corrosion Specialists, if their professional activities include suitable experience in corrosion control and cathodic protection.

1.9 This standard may not be applicable in all situations. The responsible corrosion engineer may consider alternate corrosion control methods.

Section 2: Definitions

Anode: The electrode of an electrochemical cell at which oxidation occurs. Electrons flow away from the anode in the external circuit. Corrosion usually occurs and metal ions enter the solution at the anode.

Calcareous Coating: A layer consisting of calcium carbonate and other salts deposited on the surface. When the surface is cathodically polarized as in cathodic protection, this layer is the result of the increased pH adjacent to the protected surface.

Cathode: The electrode of an electrochemical cell at which reduction is the principal reaction. Electrons flow toward the cathode in the external circuit.

Cathodic Disbondment: The destruction of adhesion between a coating and the coated surface caused by products of a cathodic reaction.

Cathodic Protection: A technique to reduce the corrosion of a metal surface by making that surface the cathode of an electrochemical cell.

⁽¹⁾ U.S. Environmental Protection Agency (EPA), 401 M Street SW, Washington, DC 20460.

⁽²⁾ American National Standards Institute (ANSI), 11 W 42nd St, New York, NY 10036.

⁽³⁾ NSF International, P.O. Box 130140, Ann Arbor, MI 48113-0140.

Coating: A liquid, liquefiable, or mastic composition that, after application to a surface, is converted into a solid protective, decorative, or functional adherent film.

Conductivity: A measure of the ability of a material to carry an electric current. In water, this depends on the total concentration of the ionized substances dissolved and the temperature at which the measurement is made. It is the reciprocal of resistivity and is usually expressed in $\mu\text{S}/\text{cm}$ ($\mu\text{mhos}/\text{cm}$).

Corrosion: The deterioration of a material, usually a metal, that results from a reaction with its environment.

Current Density: The current to or from a unit area of an electrode surface.

Electrode: A conductor used to establish contact with an electrolyte and through which current is transferred to or from an electrolyte.

Electrode Potential: The potential of an electrode in an electrolyte as measured against a reference electrode. (The electrode potential does not include any resistance losses in potential in either the electrolyte or the external circuit. It represents the reversible work to move a unit of charge from the electrode surface through the electrolyte to the reference electrode.)

Electrolyte: A chemical substance containing ions that migrate in an electric field. For the purposes of this standard, electrolyte refers to the water, including the dissolved chemicals, in the tank.

Galvanic Anode: A metal that provides sacrificial protection to another metal that is more noble when

electrically coupled in an electrolyte. This type of anode is the electron source in one type of cathodic protection.

Holiday: A discontinuity in a protective coating that exposes unprotected surface to the environment.

Impressed Current: An electric current supplied by a device employing a power source that is external to the electrode system. (An example is direct current for cathodic protection.)

Impressed Current Anode: An anode, usually composed of substantially inert materials, that is supplied with impressed current.

IR Drop: The voltage across a resistance in accordance with Ohm's Law.

Polarization: The change from the open-circuit potential as a result of current across the electrode/electrolyte interface.

Reference Electrode: An electrode whose open-circuit potential is constant under similar conditions of measurement, which is used for measuring the relative potentials of other electrodes.

Resistivity: A measure of the specific resistance of a material to the passage of electric current. It is usually expressed in ohm-centimeters (ohm-cm) and is the reciprocal of conductivity.

Tank-to-Water Potential: The voltage difference between a submerged metallic portion of the tank and the electrolyte (water), which is measured with a reference electrode in contact with the electrolyte.

Section 3: Determination of the Need for Cathodic Protection

3.1 Introduction

3.1.1 Steel tank surfaces submerged in natural waters are subject to corrosion. The methods and procedures used to control corrosion should be governed by the rate of corrosion and the cost of maintaining the tank, including the hydraulic and aesthetic effects of corrosion debris in the tank and piping.

3.1.2 All coatings are subject to damage and deterioration. Therefore, corrosion control by use of coatings alone on the submerged surfaces of a steel water storage tank is usually not possible.

3.1.3 Cathodic protection is effective in controlling corrosion only on the submerged metal surfaces.

3.2 Cathodic Protection of Coated Tanks

3.2.1. In almost all cases, natural waters are sufficiently corrosive to require the use of protective coatings and cathodic protection for corrosion control. Protective coatings and cathodic protection are synergistic with the combination of the two methods, providing a greater degree of corrosion protection than either method used alone.

3.2.2. Properly designed and maintained, cathodic protection systems can extend the useful life of the water tank and its coating system.

3.2.3 The current required for cathodic protection is lowered significantly when coatings are also used.

3.2.4 The coating system should be compatible with cathodic protection.

3.3 Cathodic Protection of Uncoated Steel Tanks

3.3.1 It is feasible to design a cathodic protection system to provide complete protection for uncoated submerged surfaces of steel tanks (see Section 4).

3.3.2 For existing steel tanks with submerged surfaces that are not coated or that have coatings in poor condition, it may be economical to rely entirely on cathodic protection.

3.4 Economic Considerations

3.4.1 Coated Tanks

The cost of cathodic protection should be compared with the cost of recoating and metal loss. Cathodic protection defers the need for coating repair and recoating for considerable time. This effectively extends the life of the coating system. In addition, cathodic protection prevents repair costs from metal loss.

3.4.2 Uncoated Tanks

It is possible to prevent metal loss in steel tanks where the surfaces are not coated or where the coating has deteriorated to the point that the surfaces can be considered uncoated. The cost of cathodic protection should be compared with the cost of metal loss, service disruption, reduction in design life, and water quality degradation.

3.5 Operational Considerations

3.5.1 Taking the tank out of service for coating maintenance or corrosion repair can be eliminated or postponed if the cathodic protection system is designed and operated properly.

3.5.2 Two benefits of keeping the tank in continuous service are system capacity and water availability for fire protection.

Section 4: Design of Impressed Current Cathodic Protection Systems

4.1 Introduction

4.1.1 This section outlines the elements that should be considered when designing impressed current cathodic protection systems for steel water storage tanks.

4.1.2 In the design of an impressed current system, the following items must be considered:

- (a) Design of the tank (accessibility, crevices, shielded areas),
- (b) Present and future condition of the coating and the generic type of coating employed,
- (c) Voltage and current capacity of the power source,
- (d) Impressed current anode material and configuration,
- (e) Impressed current anode life and ease of replacement,
- (f) Type of power source control,
- (g) Hardware,
- (h) Reference cell location(s),
- (i) Power costs,
- (j) Possible evolution of hydrogen and ventilation requirements,
- (k) Possibility of vandalism, and
- (l) Compliance with ANSI/NSF-61² in the U.S., or other governing standards outside the U.S.

4.1.3 Whenever possible, the design should be based on standard components provided by manufacturers regularly engaged in the production of impressed current cathodic protection systems for steel water storage tanks.

4.1.4 Selection of materials and system design should be accomplished in a manner to provide the best economic balance between the installation cost, the maintenance cost, and the electrical power cost over the design life of the system.

4.2 Information Required

4.2.1 Before undertaking the design of an impressed current cathodic protection system, the following information about the tank should be obtained:

- (a) Dimensions of tank, including riser if tank is elevated,
- (b) Area of submerged steel surfaces (including ladders, baffles, braces, struts, etc.),
- (c) Chemical analysis of water,
- (d) Water conductivity,
- (e) Seasonal variation in water composition,
- (f) Frequency and rate of emptying and filling the tank,
- (g) Type, specification and condition of internal coating,
- (h) Condition of internal steel surfaces exposed to the water,
- (i) Whether or not water is subject to freezing,
- (j) Average and extreme water temperatures,
- (k) Cost and availability of alternating current (AC) power,
- (l) Flow patterns, recirculation, aerators, heaters, riser pipes, and
- (m) Other pertinent information, including age and history of tank; and whether the tank is of welded, bolted, or riveted construction; and area classification.

NOTE: For bolted and riveted tanks, electrical continuity of all joining components must be ensured if corrosion control of these components by impressed current cathodic protection is to be achieved.

4.2.2 For existing tanks, an on-site corrosion evaluation, current requirement test, performance of systems in similar service, and/or laboratory testing to determine polarization characteristics may be useful.

4.3 Direct Current (DC) Power Source

4.3.1 Impressed current cathodic protection requires DC power. It is commonly obtained from transformer-rectifier units that step down AC power and convert it to DC power. However, DC power may be available from other sources such as solar cells. Units should be designed and manufactured to provide continuous, dependable operation for 10 to 20 years. Proper protective and monitoring devices, including disconnect switches; circuit breakers; output voltmeters; ammeters; and surge, lightning, and overload protection should be provided. Units should be either manually or automatically controlled over the full voltage output range.

4.3.2 Output Current Capacity

4.3.2.1 Current capacity of the unit should be based on the current requirement for cathodic protection. This current requirement is expressed in terms of current per unit area of total submerged bare surface area and depends on the corrosiveness of the water. In fresh waters, the current requirement is usually between 5 and 27 mA/m² (0.5 and 2.5 mA/ft²). Installations involving high corrosion rates, nonpotable water, and galvanic metal couples may require considerably higher current densities.

4.3.2.2 Coating the steel tank surface reduces the total current required in proportion to the effectiveness of the coating coverage. On newly coated tanks, the initial current requirement may be less than 1% of the requirement of an uncoated surface under the same conditions.

4.3.2.3 Current capacity for a coated tank should be selected so that there is sufficient capacity available even after considerable coating deterioration, typically 10 to 20% for a 20-year system design life.

4.3.3 Output Voltage Capacity

4.3.3.1 The output voltage capacity is governed by the current requirement and the circuit resistance. The voltage capacity shall be selected to overcome the wire resistance and highest anticipated anode-to-water resistance at the total current demand needed for the life of the system.

4.3.3.2 Power requirements are directly related to voltage as well as current. Therefore, operating voltage should be as low as possible (consistent with other economic considerations) and yet high enough to maintain the current required for protection.

4.3.4 Multiple-Circuit Systems

4.3.4.1 A separately controlled circuit should be provided for energizing other circuits, such as the riser anode assembly, if necessary.

4.3.4.2 Other applications for multiple system circuits might include unusual geometries, tanks with baffles, etc.

4.4 Impressed Current Anodes

4.4.1 Impressed Current Anode Configuration

4.4.1.1 Impressed current anodes shall be arranged in the tank so that protection can be provided to all surfaces without exceeding potentials (in the vicinity of the anodes) that will be detrimental to the coating system.

4.4.1.2 The number, diameter, and length of impressed current anodes shall be sufficient to achieve an acceptable circuit resistance and proper current distribution.

4.4.1.3 The design shall prevent shorting of impressed current anodes to the tank surfaces. This is particularly important in elevated tank riser pipes.

4.4.1.4 Where freezing occurs, provisions should be made for periodic replacement or for an impressed current anode installation unaffected by either freezing or falling ice. Alternatively, the tank may be operated in a manner to prevent ice accumulation on the anodes or in a solid mass across the tank, which could damage the anodes when collapsing.

4.4.2 Impressed Current Anode Materials

4.4.2.1 In designs in which only one year of anode life is required, anode materials such as aluminum alloy UNS⁽⁴⁾ A92017 may be used.

4.4.2.2 Impressed current anodes whose service life must exceed one year should be composed of more permanent material, such as mixed metal oxide-coated titanium, platinized titanium or niobium, or high-silicon cast iron. The material should be selected for its suitability in the service environment. Anode materials used in nonpotable water service may be different from those used in potable water.

4.4.2.3 Impressed current anodes, as well as all cathodic protection equipment to be installed in the tank, shall be chosen such that there is no contamination of potable water. Refer to ANSI/NSF-61² requirements.

4.4.3 Impressed Current Anode Life

The impressed current anode life depends on the consumption rate of the material selected, the weight of that material, and the current output of the system. In the case of mixed-metal oxide coated anodes, the life is dependent on the current density rating of the

coating. The design should reflect the desired anode life in the specific electrolyte.

4.5 Hardware

4.5.1 All impressed current anode support hardware and wiring should be selected for maximum economical life for the conditions inside the steel tank.

4.5.2 For vertically suspended impressed current anode systems, hand holes or mounting devices should be provided so that the anodes can be serviced without entering the tank. Any hand holes should have suitably designed weatherproof covers.

4.5.3 Horizontally oriented impressed current anode systems located below the normal water level do not normally require hand holes but may require drainage of the tank for servicing.

4.5.4 All wiring on the outside of the steel tank shall be in rigid conduit and installed with applicable codes. The use of conduit for insulated impressed current anode wiring inside the tank is not necessary.

4.5.5 Permanent reference electrodes lead wire should be brought to the rectifier location to facilitate readings. Reference cell wiring shall not be routed through the same conduit used for system DC wiring.

Section 5: Installation of Impressed Current Cathodic Protection Systems

5.1 Introduction

This section outlines installation techniques for water storage tank impressed current cathodic protection systems that protect the structure when design recommendations in Section 4 have been followed.

5.2 Construction Specifications

All construction work on impressed current cathodic protection systems shall be done in accordance with construction drawings and specifications. The drawings and specifications should be prepared by a qualified corrosion engineer, in accordance with the recommended procedures in Sections 1 and 4, and any other applicable codes. If changes are necessary, they shall be approved in writing by the engineer or owner.

5.3 Construction Supervision

5.3.1 All construction work should be performed by or under the direction of a person who is trained and qualified in the installation of impressed current cathodic protection systems in water storage tanks, and who shall verify that the installation is made in strict accordance with the drawings and specifications. Exceptions may be made only with the consent of the corrosion engineer when it can be demonstrated that the effectiveness of the system will not be impaired.

5.3.2 All deviations from original design shall be noted on record drawings.

⁽⁴⁾ Metals and Alloys in the Unified Numbering System (latest revision), a joint publication of the American Society for Testing and Materials (ASTM), 100 Barr Harbor Drive, West Conshohocken, PA 19428, and the American Society of Automotive Engineers Inc. (SAE), 400 Commonwealth Drive, Warrendale, PA 15096.

5.4 Inspection and Handling

5.4.1 The DC power source shall be inspected to ensure that internal connections are mechanically secure and that no damage is apparent. Rating of the DC power source shall comply with Paragraph 4.3.1 and the construction specifications.

5.4.2 Impressed current anodes shall be inspected for conformance to specifications for correct anode material and size, length of lead wire, method of wire connection, and damage to any portion of the assembly. Damage to anodes during handling and installation must be avoided. All wire should be carefully inspected for insulation defects, and damage to insulation must be avoided. If defects are not repaired, the anode must be rejected. Damage to insulation may result in premature failure of the wire.

5.5 Installation

5.5.1 The power supply should be installed so that the possibility of damage or vandalism is minimized.

5.5.2 Construction practices shall conform to all applicable local and national codes.

5.5.3 All power sources which provide AC service to a CP system should have a disconnect built into the equipment and shall also have a separate, external disconnect. Dedicated AC service will allow the equipment to be isolated for maintenance and lockout.

5.5.4 The power supply should be installed at a convenient height above the ground so that it may be serviced readily unless other factors such as vandalism, flooding, etc., apply.

5.5.5 The positive cable and anode leads are especially critical to the operation of the system. It is imperative that insulation remains intact. The entire cable and all connections must be waterproof. The cable must be protected from abrasion and sharp objects. There shall be no metal-to-metal contact between the positive cable and the tank structure or conduit. The positive cable(s) must be connected to the impressed current anodes, and the negative cable(s) must be properly connected to the tank.

5.5.6 Underwater splices on the positive cable should be avoided unless required by in-service installation or repairs to the system. Connections between the positive cable and anode leads must be mechanically secure and electrically conductive. These connections must be sealed to prevent moisture penetration.

Section 6: Criteria for Cathodic Protection and Measurement Procedures

6.1 Introduction

6.1.1 This section describes the criteria for impressed current cathodic protection along with measurement techniques which, when followed, provide virtually complete corrosion control on the internal, submerged surfaces of steel water storage tanks.

6.1.2 The criteria in Paragraph 6.2 have been developed through laboratory experiments and have been verified by evaluating data obtained from successfully operated impressed current cathodic protection systems. It is not intended that the corrosion engineer be limited to these criteria if it can be demonstrated that corrosion control can be otherwise achieved.

6.1.3 Measurement of the voltage between the tank and a reference electrode placed in the water shall be used to determine whether adequate cathodic protection has been achieved. This voltage is referred to as tank-to-water potential.

6.2 Criteria

6.2.1 A negative, polarized tank-to-water potential of at least -850 mV relative to a saturated copper/copper sulfate reference electrode (CSE); or

6.2.2 A minimum of 100 mV of cathodic polarization between the tank surface and a stable reference electrode contacting the electrolyte. The formation or decay of polarization can be measured to satisfy this criterion.

CAUTIONARY NOTE: The 100 mV polarization shift criterion is only applicable to steel water tanks not having corrosion cells caused by connection to more noble metals such as copper, brass, or passive stainless steel (e.g., heated water tanks in which the submerged heater tubes are constructed of copper or brass, and are electrically continuous with the submerged steel tank).

6.3 Measurement Procedures

6.3.1 In order to observe the polarized tank-to-water potential, the IR drop error must be eliminated from the measurement. Among the methods used to eliminate IR drop error are (1) measuring the tank-to-water potential with the protective current instantaneously interrupted and (2) interrupting the electrical connection between the tank and a submerged coupon(s) and immediately measuring the coupon-to-water potential.

6.3.2 A sufficient number of potential measurements should be taken to determine that adequate protection

is being achieved throughout the steel tank, especially at the most difficult-to-protect locations. In practice, potential profiles of the submerged steel at intervals along the wall and floor during initial adjustment should be taken.

6.3.3 A reference electrode other than a CSE may be used. The potential representing the minimum protective value shall be equivalent to the -850 mV value for the CSE. For example, when a saturated potassium chloride (KCl) calomel reference is used, the appropriate value is -780 mV.

6.4 Cautionary Note

NOTE: Cathodic protection for well-coated tanks should only be designed, installed, and energized under the direction of a corrosion engineer with coating and cathodic

protection experience. The coating system must be compatible with cathodic protection and must demonstrate resistance to cathodic disbondment. It has been observed that some coatings may not be compatible with cathodic protection and may be damaged by excessive currents. While there is currently no agreement regarding the tank-to-water potential at which damage occurs, coating failures have been observed at polarized potentials more negative than -1.1 V to a CSE.

The cathodic protection system should be energized as soon as possible after the tank is filled with water. Waiting until the coating warranty period has expired only subjects the tank to additional deterioration from corrosion and may lead to severe pitting attack at holidays in the coating.

Section 7: Automatic Impressed Current Systems

7.1 Introduction

7.1.1 This section describes practices for the automatic regulation of cathodic protection current to maintain a pre-selected tank-to-water potential. The pre-selected tank-to-water potential should be in accordance with Section 6.

7.1.2 The use of manually controlled cathodic protection systems is acceptable and may be desirable depending on specific structure conditions as determined by the design corrosion engineer.

7.2 General

7.2.1 Cathodic protection current requirements for protection in accordance with the criteria in Paragraph 6.2 can vary with coating deterioration, accumulation of polarization films, temperature, water level, water velocity, water composition, dissolved oxygen, and other conditions. If the proper tank-to-water potential is maintained, the effectiveness of corrosion control is assured.

7.2.2 Automatic cathodic protection systems are designed to adjust the current output so that the tank-to-water potential remains at a preset constant value required for effective corrosion control. For some impressed current anode configurations, automatic cathodic protection systems may be necessary. Consideration should be given to providing current-limiting devices to prevent excessive current outputs that may be harmful to the coating (see Paragraph 6.4).

7.3 Components

7.3.1 Power Source Unit

7.3.1.1 The power source used to energize the cathodic protection system shall be capable of varying the current output from 0 to 100% of its rated capacity.

7.3.1.2 The tank-to-water potential used to control the current output shall be derived from a reference electrode or electrodes properly placed in the water tank.

7.3.1.3 The tank-to-water potential used to control the current output shall be consistent with the criteria given in Paragraph 6.2.

7.3.1.4 The power source shall be capable of varying the current output in order to maintain the tank-to-water potential within ± 25 mV of the selected value.

7.3.2 Reference Electrode(s)

The reference electrode(s), from which the tank-to-water potential is obtained for controlling the current output, must be continually immersed. The reference electrode(s) should have a potential difference of less than ± 10 mV when compared with a new electrode. When the potential difference exceeds ± 20 mV, the electrode shall be replaced.

Section 8: Operation and Maintenance

8.1 This section outlines the procedures necessary for the effective operation and maintenance of impressed current cathodic protection systems.

8.2 Operation

8.2.1 For an impressed current cathodic protection system to control corrosion effectively, it must be kept in continuous operation and maintain a level of protection that satisfies the criteria.

8.2.2 When the system is energized, it shall be adjusted to obtain the desired tank-to-water potential in accordance with Paragraph 6.2.

8.3 Maintenance

8.3.1 Monthly

8.3.1.1 The power unit should be inspected at least once each month to verify that it is operating correctly and that the proper tank-to-water potentials are being maintained.

8.3.1.2 In a manually controlled system, the voltage and current of the power unit and the tank-to-water potential using permanent reference electrodes, if any, shall be measured. If the tank-to-water potential is outside the proper range, the cause shall be determined and adjustments made accordingly.

8.3.1.3 In an automatic system, the tank-to-water potential shall be measured to determine that the system is maintaining the predetermined potential within the tolerance indicated in Paragraph 7.3.1.4. A log shall be maintained to establish an operating profile and shall be referred to when making regular inspections. If the potential is outside the proper range, the cause shall be determined. Among the possible causes of potential drift are wiring faults exceeding the current capacity of the unit or a defective reference electrode. Among the possible causes of a change in current are defective reference electrode, wiring faults, establishment of calcareous deposits, and coating deterioration. The first two require immediate replacement or repair. The third normally requires a decrease and the fourth, an increase, in current requirement.

8.3.1.4 More frequent inspection of the systems may be desirable in critically corrosive situations, when the tank has previously suffered extensive metal loss as a result of corrosion or when there are highly variable conditions.

8.3.1.5 Remote monitoring equipment can aid in the collection of the data, reduce monitoring costs, and allow for more frequent, real-time data collection during a variety of tank operations, such as filling and sudden drops in water level.

8.3.2 Annual

8.3.2.1 All impressed current cathodic protection system components should be completely inspected annually. This inspection should include potential profile testing with portable instruments to ensure that the system is operating properly. The power source, controls, anodes, wiring, and reference electrodes should be examined and replaced as required.

8.3.2.2 Power Source—The power unit is usually designed for long life with little maintenance required. The monthly inspection indicated in Paragraph 8.3.1.1 should reveal any failures requiring repairs and replacements. Annual maintenance should include removing debris at the openings required for cooling, checking that all connections and wiring are secure and unaffected by corrosion, inspecting the electrical grounding, and painting of cabinets and housings, if required.

8.3.2.3 Impressed Current Anodes and Wiring

8.3.2.3.1 In systems using impressed current anodes designed for one-year life (see Paragraph 4.4.2.1), all anodes shall be replaced annually (or according to design life). In water storage tanks subject to icing conditions, anodes should be replaced in the spring after the opportunity for freezing has passed. Alternatively, the tank may be operated in a manner to raise and lower the water level during freezing conditions and thereby extend anode life.

8.3.2.3.2 Lowering the water level provides an opportunity to inspect the interior surface of the tank. If the tank is coated, the condition of the coating should be recorded. Also, the presence of either corrosion or calcareous deposits should be recorded.

8.3.2.4 Reference Electrodes

8.3.2.4.1 Reference electrodes and connecting wire should be inspected to determine whether they are physically capable of operating until the next annual inspection. Any breaks in the wiring insulation must be repaired. If insulation has

deteriorated, wiring shall be replaced. It is important that all wiring and connections to reference electrodes be completely insulated.

8.4 Records

8.4.1 Tank Information

8.4.1.1 Complete information and history of the tank itself should be recorded, including:

- (a) Dimensions, configuration, and capacity,
- (b) Tank contractor,
- (c) Date of erection,
- (d) Materials of construction,
- (e) Original coating, including system, surface preparation, and materials,
- (f) Subsequent coatings and dates of coating,
- (g) History of any structural repairs,
- (h) Costs associated with erection and maintenance of the tank,
- (i) Tank location, and
- (j) Warranty dates on coatings and cathodic protection.

8.4.2 Water Information

8.4.2.1 Complete information about the water stored in the tank should be recorded. This information should include both the chemical and electrical characteristics as well as information about variations in these characteristics that occur throughout the year as a result of natural causes, disinfection, and water treatment.

8.4.2.2 Operational information about frequency of draining, cleaning, and filling should be recorded.

8.4.3 Cathodic Protection System

8.4.3.1 Complete information about the installation and design should be recorded, including:

- (a) Power source capacity, both AC and DC,
- (b) Number and configuration of impressed current anodes,
- (c) Impressed current anode material and design life,
- (d) Wiring and anode suspension,
- (e) Electrical schematic diagrams, and
- (f) Date of energizing and initial current and voltage settings.

8.4.3.2 Maintenance records should be kept, including:

- (a) Tabulation of monthly measurements of impressed current voltage and current of the power source and tank-to-water potentials. Water surface elevations at the time of testing should also be recorded.
- (b) Reports of annual inspections.
- (c) All repairs and additions.
- (d) The cost of all maintenance, including coating, cathodic protection inspection, etc.

References

1. NACE Standard RP0196 (latest revision), "Galvanic Anode Cathodic Protection of Internal Submerged Surfaces of Steel Water Storage Tanks" (Houston, TX: NACE).

2. NSF-61 (latest revision), "Drinking Water System Components" (Ann Arbor, MI: NSF International).

Standard Recommended Practice

Mitigation of Alternating Current and Lightning Effects on Metallic Structures and Corrosion Control Systems

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Reaffirmed 2000-09-19
Approved July 1977
Revised July 1983
Revised March 1995
NACE International
1440 South Creek Drive
Houston, Texas 77084-4906
+ 1 (281) 228-6200
ISBN 1-57590-116-1
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Foreword

This standard recommended practice presents guidelines and procedures for use during design, construction, operation, and maintenance of metallic structures and corrosion control systems used to mitigate the effects of lightning and overhead alternating current (AC) power transmission systems. This standard is not intended to supersede or replace existing electrical safety standards. As shared right-of-way and utility corridor practices become more common, AC influence on adjacent metallic structures has greater significance and personnel safety becomes of greater concern. This standard addresses problems primarily caused by proximity of metallic structures to AC-powered transmission systems.

The hazards of lightning effects and alternating current effects on aboveground pipelines, while strung along the right-of-way prior to installation in the ground, is of particular importance to pipeline construction crews. The effects of overhead AC power lines on buried pipelines is of particular concern to operators of aboveground appurtenances and cathodic protection testers, as well as maintenance personnel working on the pipeline.

Some controversy arose in the 1995 issue of this standard regarding the shock hazard stated in Section 5, Paragraph 5.2.1.1 and elsewhere in this standard. The reason for a more conservative value is that early work by George Bodier at Columbia University and by other investigators has shown that the average hand-to-hand or hand-to-foot resistance for an adult male human body can range between 600 ohms and 10,000 ohms.¹ A reasonable safe value for the purpose of estimating body currents is 1,500 ohms hand-to-hand or hand-to-foot. In other work by K.S. Gelges and C.F. Dalziel on muscular contraction, the inability to release contact would occur in the range of 6 to 20 milliamperes for adult males.² Ten milliamperes hand-to-hand or hand-to-foot is generally established as the absolute maximum safe let-go current. Conservative design would use an even lower value. Fifteen volts AC impressed across a 1,500-ohm load would yield a current flow of 10 milliamperes; thus the criterion within this standard is set at 15 volts. Prudent design would suggest an even lower value under certain circumstances.

This standard was originally published in July 1977 and was technically revised in 1983 and 1995. NACE International continues to recognize the need for a standard on this subject. Future development and field experience should provide additional information, procedures, and devices for Specific Technology Group (STG) 05 to consider in future revisions of this standard. This edition of the standard was reaffirmed by Unit Committee T-10B on Interference Problems. The NACE technical committee structure changed in 2000, following the reaffirmation of this standard. This standard is issued in 2000 by NACE International under the auspices of STG 05 on Cathodic/Anodic Protection.

In NACE standard, the terms *shall*, *must*, *should* and *may* are used in accordance with the definitions of these terms in the *NACE Publications Style Manual*, 4th ed., Paragraph 7.4.1.9. *Shall* and *must* are used to state mandatory requirements. *Should* is used that which is considered good and is recommended but is not absolutely mandatory. *May* is used to state that which is considered optional.

**NACE International
Standard
Recommended Practice**

**Mitigation of Alternating Current and Lightning Effects
on Metallic Structures and Corrosion Control Systems**

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Section 1: General

1.1 This standard presents acknowledged practices for the mitigation of alternating current (AC) and lightning effects on metallic structures and corrosion control systems.

1.2 This standard covers the procedures for determining the level of AC influence and lightning effects to which an existing metallic structure may be subjected and outlines design, installation, maintenance, and testing procedures for cathodic protection systems on structures subject to AC influence.

1.3 This standard does not designate procedures for any specific situation. The provisions of this standard should

be applied under the direction of competent persons, who, by reason of knowledge of the physical sciences and the principles of engineering and mathematics, acquired by professional education and related practical experience, are qualified to engage in the practice of corrosion control on metallic structures. Such persons may be registered professional engineers or persons recognized as being qualified and certified as corrosion specialists by NACE International if their professional activities include suitable experience in corrosion control on metallic structures.

1.4 This standard should be used in conjunction with the references contained herein.

Section 2: Definitions

2.1 Definitions presented in this standard pertain to the application of this standard only. Reference should be made to other industry standards where appropriate.

AC Exposure: Alternating voltages and currents induced on a structure because of the alternating current (AC) power system.

AC Power Structures: The structures associated with AC power systems.

AC Power System: The components associated with the generation, transmission, and distribution of alternating current.

Affected Structure: Pipes, cables, conduits, or other metallic structures exposed to the effects of alternating current and/or lightning.

Bond: A low-impedance connection (usually metallic) provided for electrical continuity.

Breakdown Potential: A voltage potential in excess of the rated voltage that causes the destruction of a barrier film, coating, or other insulating material.

Capacitive Coupling: The association of two or more circuits with one another by means of a capacitance mutual to the circuits.

Coupling: The association of two or more circuits or systems in such a way that energy may be transferred from one to another.

Dead-Front Construction: A type of construction in which the energized components are recessed or covered to preclude the possibility of accidental contact with elements having electrical potential.

Direct Current (DC) Decoupling Device: A device used in electrical circuits that allows the flow of AC in both directions and stops or substantially reduces the flow of DC.

Earth Current: Electric current flowing in the earth.

Electric Field: One of the elementary energy fields in nature. It is found in the vicinity of an electrically charged body.

Electric Potential: The voltage difference between two points.

Electric Shield: A housing, screen, or other object, usually electrically conductive, which is installed to substantially reduce the effects of electric fields on one side caused by devices or circuits on the other side of the shield.

Electrolytic Grounding Cell: A DC decoupling device consisting of two or more electrodes, commonly made of zinc, installed at a fixed spacing and resistively coupled through a prepared backfill mixture.

Fault Current: A current that flows from one conductor to ground or to another conductor due to an abnormal connection (including an arc) between the two. A fault current flowing to ground may be called a ground fault current.

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Ground: An electrical connection to earth.

Ground Current: Current flowing to or from earth in a grounding circuit.

Grounded: Connected to earth or to some extensive conducting body that serves instead of the earth, whether the connection is intentional or accidental.

Ground Electrode Resistance: The ohmic resistance between a grounding electrode and remote earth.

Ground Mat (Gradient Control Mat): A system of bare conductors on or below the surface of the earth, so arranged and interconnected as to provide an area of equal potential within the range of step distances. (Metallic plates and grating of suitable area are common forms of ground mats.)

Grounding Grid: A system of grounding electrodes consisting of interconnected bare conductors buried in the earth to provide a common electrical ground.

Inductive Coupling: The association of two or more circuits with one another by means of the mutual inductance of the circuits.

Lightning: An electric discharge that occurs in the atmosphere between clouds or between clouds and the earth.

Load Current: The current in an AC power system under normal operating conditions.

Magnetic Field: One of the elementary energy fields in nature. It occurs in the vicinity of a magnetic body or current-carrying medium.

Polarization Cell: A DC decoupling device consisting of two or more pairs of inert metallic plates immersed in an aqueous electrolyte. The electrical characteristics of the polarization cell are high resistance to DC potentials and low impedance of AC.

Potential: See Electric Potential.

Potential Gradient: Change in the potential with respect to distance.

Reclosing Procedure: A procedure which normally takes place automatically, whereby the circuit breaker system protecting a transmission line, generator, etc., recloses one or more times after it has tripped because of abnormal conditions such as surges, faults, lightning strikes, etc.

Reference Electrode: An electrode whose open-circuit potential is constant under similar conditions of measurement, which is used for measuring the relative potentials of other electrodes.

Remote Earth: A location on the earth far enough from the affected structure that the soil potential gradients associated with currents entering the earth from the affected structure are insignificant.

Resistive Coupling: The association of two or more circuits with one another by means of resistance (metallic or electrolytic) between the circuits.

Shock Hazard: A condition considered to exist at an accessible part in a circuit between the part and ground or other accessible part if the open-circuit AC potential is more than 15 V (root mean square [rms]) and capable of delivering 5 mA or more.

Step Potential: The voltage difference between two points on the earth's surface separated by a distance of one pace, which is assumed to be one meter, calculated in the direction of maximum potential gradient.

Surface Potential Gradient: The slope of a potential profile, the path of which intersects equipotential lines at right angles.

Switching Surge: The transient wave of potential and current in an electric system that results from the sudden change of current flow caused by a switching operation such as the opening or closing of a circuit breaker.

Touch Potential: The potential difference between a metallic structure and a point on the earth's surface separated by a distance equal to the normal maximum horizontal reach of a human (approximately 1.0 m [3.3 ft]).

Section 3: Exposures and Effects of Alternating Current and Lightning

3.1 Introduction

3.1.1 This section outlines the physical phenomena by which AC, AC power systems, and lightning may affect metallic structures.

3.2 Resistive Coupling (Electrolytic)

3.2.1 Grounded structures of an AC power system share an electrolytic environment with other underground or submerged structures. Coupling effects may transfer AC energy to a metallic structure in the earth in the form of alternating current or potential. Whenever a power system with a grounded neutral has unbalanced conditions, current may flow in the earth. Substantial currents in the earth may result from phase-to-phase or phase-to-ground faults. A metallic structure in the earth may carry part of this current. Also, a structure in the earth coated with an insulating material may develop a significant AC potential across the coating.

3.3 Capacitive Coupling

3.3.1 The electric field associated with potentials on power conductors can develop a potential on an inadequately grounded structure in the vicinity of the power system. The potential that the structure attains because of capacitive coupling varies with the power conductor potential and depends on many factors, including the geometric configurations of the structures involved. During construction, when the structure is aboveground or in an open trench, it may reach a dangerously high potential. When the structure is buried or submerged, the capacitive coupling effect usually is not significant unless (1) the soil resistivity is high, (2) the structure is electrically isolated, or (3) the structure is very long.

3.4 Inductive Coupling

3.4.1 AC current flow in power conductors produces an alternating magnetic field around these conductors. Thus, an AC potential can be induced in an adjacent structure within this magnetic field, and current may flow in that structure. The magnitude of the induced potential depends on many factors including the overall geometric configuration of the structures involved, the magnitude of the current in the power circuit, and any current imbalance. If the

currents in a three-phase power system are equal (balanced) and the affected structure is equidistant from each of the conductors, the total induced voltage is zero. This, however, is seldom the case, and induced AC voltage is usually present on the affected structure. Greater electromagnetically induced potentials may occur during a phase-to-ground or phase-to-phase fault in multiphase circuits because of the higher magnitude of fault current in these systems. The leakage conductance to ground, caused by the resistive coupling of the affected structure, allows AC current to flow between that structure and earth. This phenomenon, combined with other factors, results in different values of AC structure-to-electrolyte potential along the affected structure. The higher the dielectric strength and resistance of the coating and the higher the soil resistivity, the greater the induced AC potential.

3.5 Power Arc

3.5.1 During a fault to ground on an AC power system, the AC power structures and surrounding earth may develop a high potential with reference to remote earth. A long metallic structure, whether coated or bare, tends to remain at remote earth potential. If the resulting potential to which the structure is subjected exceeds breakdown potential of any circuit element, a power arc can occur and damage the circuit elements. Elements of specific concern include coatings, isolating fittings, bonds, lightning arresters, and cathodic protection facilities.

3.6 Lightning

3.6.1 Lightning strikes on the power system can initiate fault current conditions. Lightning strikes to a structure or to earth in the vicinity of a structure can produce electrical effects similar to those caused by AC fault currents. Lightning may strike a metallic structure at some point remote from AC power systems, also with deleterious effects.

3.7 Switching Surges or Other Transients

3.7.1 A switching surge or other transient may generate abnormally high currents or potentials on a power system, causing a momentary increase in inductive and capacitive coupling on the affected structures.

Section 4: Design Considerations for Protective Devices

4.1 Introduction

4.1.1 This section describes various protective devices used to help mitigate AC effects on metallic structures, minimize damage to the structures, and reduce the electrical hazard to people coming in contact with these structures.

4.1.2 The methods listed can be used to mitigate the problems of power arcing, lightning arcing, resistive coupling, inductive coupling, and capacitive coupling.^{3, 4, 5}

4.2 Electrical Shields

4.2.1 Shields are intended to protect the structures from arcing effects that may be produced in the earth between AC power systems and affected metallic structures, thus reducing the possibility of puncturing the coating and/or structure under surge conditions.

4.2.2 Among the factors that influence the design of electrical shields are the extent to which the structure is affected and the magnitude of the electrical potential between the structure and earth. These factors vary from one location to another and must be calculated or determined for each specific location.

4.2.3 Shields may consist of one or more electrodes installed parallel to and/or encircling an affected structure at specific locations or along its entire length. Some types of shields, such as those made of an anodic material, must be electrically connected to the affected structure. Shields of the parallel or encircling anode type shall be connected to the structure at least at the end points of the shield. Shields constructed of materials that are cathodic to the protected structure must be connected to the structure through a DC decoupling device.

4.2.4 Other types of electrical shields can be designed for protection against surges on miscellaneous underground or aboveground structures. A long, buried, bare conductor can be used effectively as a shield.

4.3 Grounding Mats

4.3.1 Grounding mats, bonded to the structure, are used to reduce electrical step and touch potentials in areas where people may come in contact with a structure subject to hazardous potentials. Permanent grounding mats bonded to the structure may be used at valves, metallic vents, cathodic

protection test stations, and other aboveground metallic and nonmetallic appurtenances where electrical contact with the affected structure is possible.

4.3.2 Grounding mats should be large enough to extend through and beyond the entire area on which people may be standing when contacting the affected structure. They should be installed close enough to the surface so that step and touch potentials are adequately reduced for individuals coming in contact with the structure.⁶

4.3.3 Grounding mats, regardless of materials of construction, must be bonded to the structure, preferably at more than one point. If cathodic protection of the structure becomes difficult because of shielding, a DC decoupling device may be installed. Connections to the structure should be made aboveground to allow a means of testing for effectiveness of the grounding mat in reducing AC potentials and of its effects on the cathodic protection system. Care should be taken to prevent the possible establishment of detrimental galvanic cells between the grounding mat and structures that are not cathodically protected.

4.3.4 A bed of clean, well-drained gravel can reduce the shock hazard associated with step and touch potentials. The thickness of the bed should be no less than 8 cm (3 in.). Gravel should be a minimum of 1.3 cm (0.5 in.) in diameter. The hazards of step potentials at the edge of a mat may be mitigated by extending the gravel beyond the perimeter of the grounding mat.

4.4 Independent Structure Grounds

4.4.1 Wherever a metallic structure that is not electrically connected to an existing grounded structure is installed, it shall have an independent grounding system. This grounding system may consist of one or more ground rods and interconnecting wires. Care shall be taken to properly interconnect all components of the structure to be grounded. Factors considered in the design of the grounding system of an independent structure include the resistivity of the soil and the magnitude of the induced potential and current which the designer expects the structure to encounter under all possible conditions.

4.4.2 When an independent metallic structure or its grounding system is in close proximity to an existing grounded structure, an electrical hazard may develop

for any person contacting both structures and/or their grounds simultaneously. In such cases, both grounding systems should be connected, either directly or through a DC decoupling device, unless it is determined that such a connection is undesirable. For more details on designing systems for independent structures, see IEEE⁽¹⁾ Standard 80.³

4.5 Bonding to Existing Structures

4.5.1 One available means of reducing induced AC potentials on a structure involves bonding the structure to the power system ground through adequately sized cables and decoupling devices. Such bonds may, under fault conditions, contribute to increased potentials and currents on the affected structure for the duration of the fault. If the bonded structure is aboveground, or well insulated from earth, elevated potentials may be created and exist temporarily along the entire length of the bonded structure. In such instances, additional protective devices may be required outside the immediate area of the origin of electrical effects. Close coordination should be maintained with all other utilities in the area and especially with those utilities to which bond connections are proposed. The corresponding utilities shall be notified in advance of the need to bond to their structures and shall be furnished with details of the proposed bonding arrangements. A utility may prefer to have the connection to its structures made by its own personnel. Other methods of reducing AC potentials should be considered before committing to this one. The increased hazards during fault conditions and extra installation requirements may make this method questionable from safety and economic perspectives.

4.6 Distributed Anodes

4.6.1 Whenever distributed galvanic anodes are used as part of the grounding system to reduce the AC potential between a structure and earth, they should be installed in close proximity to the protected structure and away from power system grounds. Connecting anodes directly to the affected structure, without test connections, may be desirable. Direct connection reduces the number of points at which people can come in contact with the structure, and offers the shortest path to ground. Should it be desirable, for measurement purposes, to open the circuit between the distributed grounding system and the structure, the test lead connection should be made in an accessible, dead-front test box. When galvanic anodes are used as part of a grounding system, the useful life of the electrode material should be considered. Dissipation of the anode material increases the grounding system resistance.

4.7 Casings

4.7.1 Bare or poorly coated casings may be deliberately connected to a coated structure, through a DC decoupling device, to lower the impedance of the structure to earth during surge conditions and to avoid arcing between the structure and the casing.

4.8 Connector (Electrical and Mechanical) and Conductor Sizes

4.8.1 All anodes, bonds, grounding devices, and jumpers must have secure, reliable, low-resistance connections to themselves and to the devices to which they are attached. Structure members with rigid bolted, riveted, or welded connections may be used in lieu of a bonding cable for part or all of the circuit. For adequate sizing of bonding cables, refer to Table 1 and Figures 1, 2, and 3. All cables, connections, and structural members should be capable of withstanding the maximum anticipated magnitude and duration of the surge or fault currents.

4.8.2 Mechanical connections for the installation of permanent protective devices should be avoided, where practical, except where they can be inspected, tested, and maintained in approved aboveground enclosures. Where practical, field connections to the structure and/or grounding device should be made by the exothermic welding process. However, compression-type connectors may be used for splices on connecting wires. Mechanical connectors may be used for temporary protective measures, but extreme care should be taken to avoid high-resistance contacts. Soft soldered connections are not acceptable in grounding circuits.

Figure 1 is based on the assumption that no heat is radiated or conducted from the cable to the surrounding media during a fault period. Electrical energy released in the cable equals the heat energy absorbed by the cable. This is illustrated in Equation (1):

$$I^2 R t = 1,055 Q \text{ (watt seconds = BTU)} \quad (1)$$

where I = fault current in amperes, R = average AC resistance (in ohms) of conductor over temperature range T_1 to T_2 (in degrees Fahrenheit), t = fault duration in seconds, and Q = heat energy in British Thermal Units. Q is calculated using Equation (2):

$$Q = CM (T_2 - T_1) \text{ (Thermodynamics)} \quad (2)$$

⁽¹⁾ Institute of Electrical and Electronics Engineers (IEEE), 3 Park Avenue, 17th Floor., New York, NY 10016-5997.

Table 1: Maximum 60 Hz Fault Currents—Grounding Cables^(A)

Cable Size AWG ^(B)	Fault Time Cycles	rms Amperes		Cable Size AWG	Fault Time Cycles	rms Amperes	
		Copper	Aluminum			Copper	Aluminum
1	15	10,550	6,500	3/0	15	26,500	16,500
	30	7,500	4,600		30	18,500	16,500
	60	5,300	3,200		60	13,000	8,000
1/0	15	16,500	10,500	4/0	15	30,000	21,000
	30	11,500	7,500		30	21,000	15,000
	60	8,000	5,300		60	15,000	10,000
2/0	15	21,000	13,000	250 MCM	15	35,000	25,000
	30	15,000	9,000		30	25,000	17,500
	60	10,000	6,500				

^(A) Based on 30°C (86°F) ambient and a total temperature of 175°C (347°F) established by Insulated Cable Engineers Association (ICEA)⁽²⁾ for short-circuit characteristic calculations for power cables. Values are approximately 58% of fusing currents.

^(B) American Wire Gauge (AWG)

where C = average specific heat in BTU/([lb][°F]) of annealed soft-drawn copper over the temperature range T₁ to T₂, M = mass of copper in pounds, T₁ and T₂ = initial and final temperatures respectively in degrees Fahrenheit. Figure 1 was developed using C = 0.104 BTU/([lb][°F]), T₁ = 68°F, and T₂ = 1,300°F.⁽³⁾ Typical resistance values are shown in Table 2.

4.9 Isolating Joints

4.9.1 Isolating joints may be installed to divide the structure into shorter electrical sections or to isolate a section adjacent to an AC power system from the remainder of the structure. Isolating joints installed in areas where a possibility of damage exists because of induced AC potentials or fault currents should have lightning arresters, polarization cells, electrolytic grounding cells, or similar protective devices installed across the joints. The threshold voltage characteristics of lightning arresters should be considered, and installation should include personnel protection such as dead-front construction. (The AC and DC isolation provided by isolating joints is not provided during the conducting mode of some protective devices.)

4.10 Electrolytic Grounding Cells, Polarization Cells, and Other Devices

4.10.1 The coordinated selection and installation of electrolytic grounding cells, polarization cells (2.5-V DC maximum threshold), or other devices between the affected structure and suitable grounds should be considered where arcing and induced AC potentials could develop. These devices may eliminate or

greatly reduce the induced potentials resulting during normal operation or surge conditions and also reduce the possibility of arcing and structure puncture.

4.10.2 Where electrolytic grounding cells, polarization cells (2.5-V DC maximum threshold), or other devices are used, they should be properly sized, spaced, and physically secured in a manner that safely conducts the maximum amount of anticipated surge current. Cables connecting these devices to the structures shall be properly sized as described in Paragraph 4.8.1. Cables should be kept as short and straight as possible. An adequately sized shunting circuit should be provided to permit electrical isolation of the grounding device during testing and maintenance.

4.11 Lightning Arresters and Metal Oxide Varistors (MOVs)

4.11.1 Lightning arresters and MOVs may be used between structures and across pipeline electrical isolating devices. However, one restriction to the use of lightning arresters is that a potential difference has to develop before the arrester conducts. With certain types of arresters, this potential may be high enough to become hazardous to people coming in contact with the arrester. When lightning arresters are used, they must be connected to the structure through adequately sized cables as described in Paragraph 4.8.1. Lightning arresters should always be provided with a reliable, low-resistance ground connection. They should be located close to the structure being protected and have a short, straight ground path. An adequately

⁽²⁾ Insulated Cable Engineers Association (ICEA), P.O. Box 440, South Yarmouth, MA 02664.

⁽³⁾ To calculate Q using metric units:

1. Find C (average specific heat) in "(cal/g)(°C)" or "BTU/([lb][°F])" from handbook tables.
2. Substitute M (mass) with "0.002205 x M_(g)" where M_(g) = mass of copper in grams.
3. Substitute T₁ = (°C₁ + 17.78)(1.8) and T₂ = (°C₂ + 17.78)(1.8).

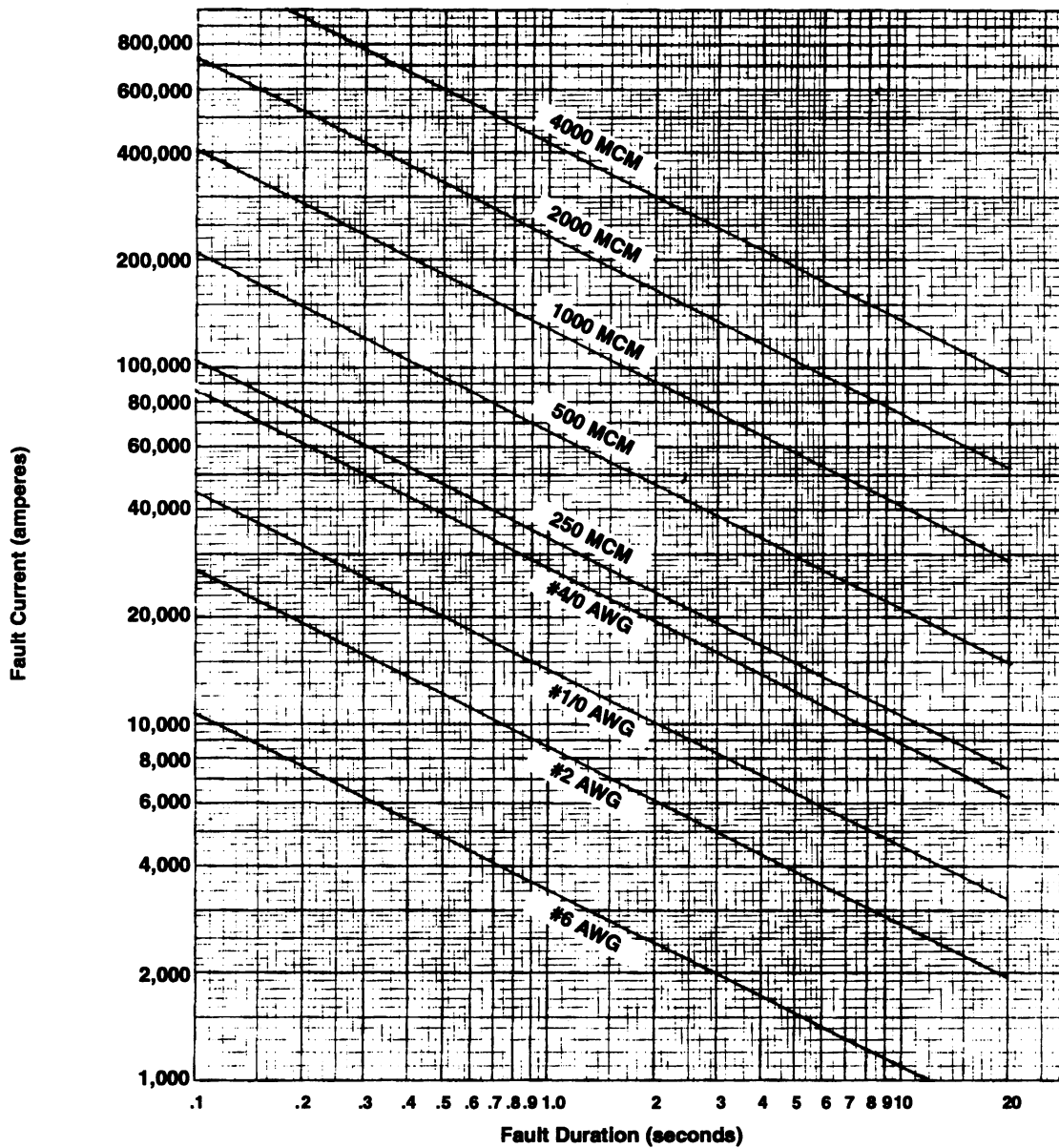


Figure 1—Approximate current required to raise the temperature of stranded annealed soft-drawn copper cable 684°C (1,232°F) above an ambient temperature of 20°C (68°F)

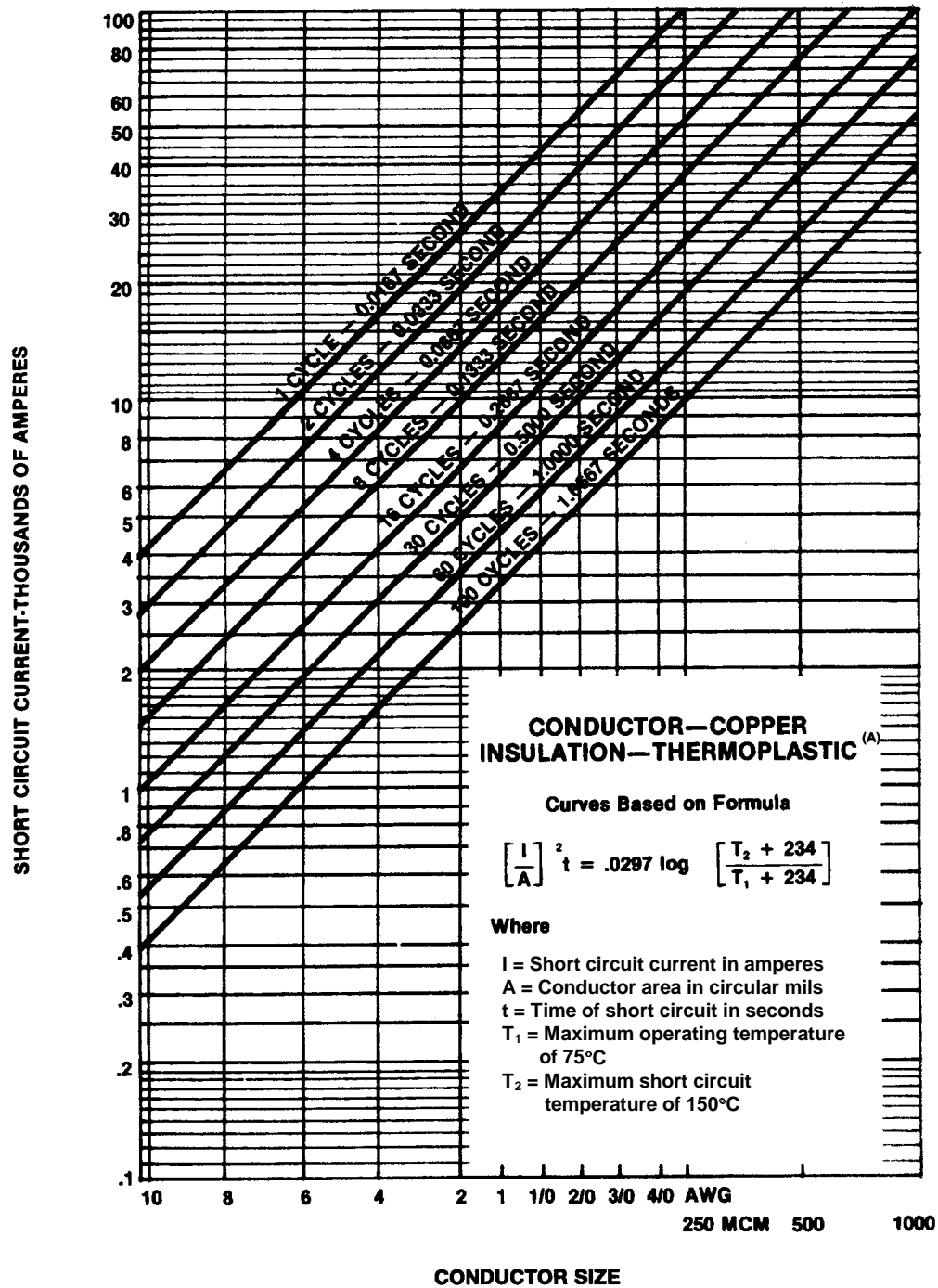


Figure 2 — Allowable short circuit currents for insulated copper conductors.

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^(A) To calculate this formula using metric units, change A to metric values as indicated in Table A1, Appendix A.

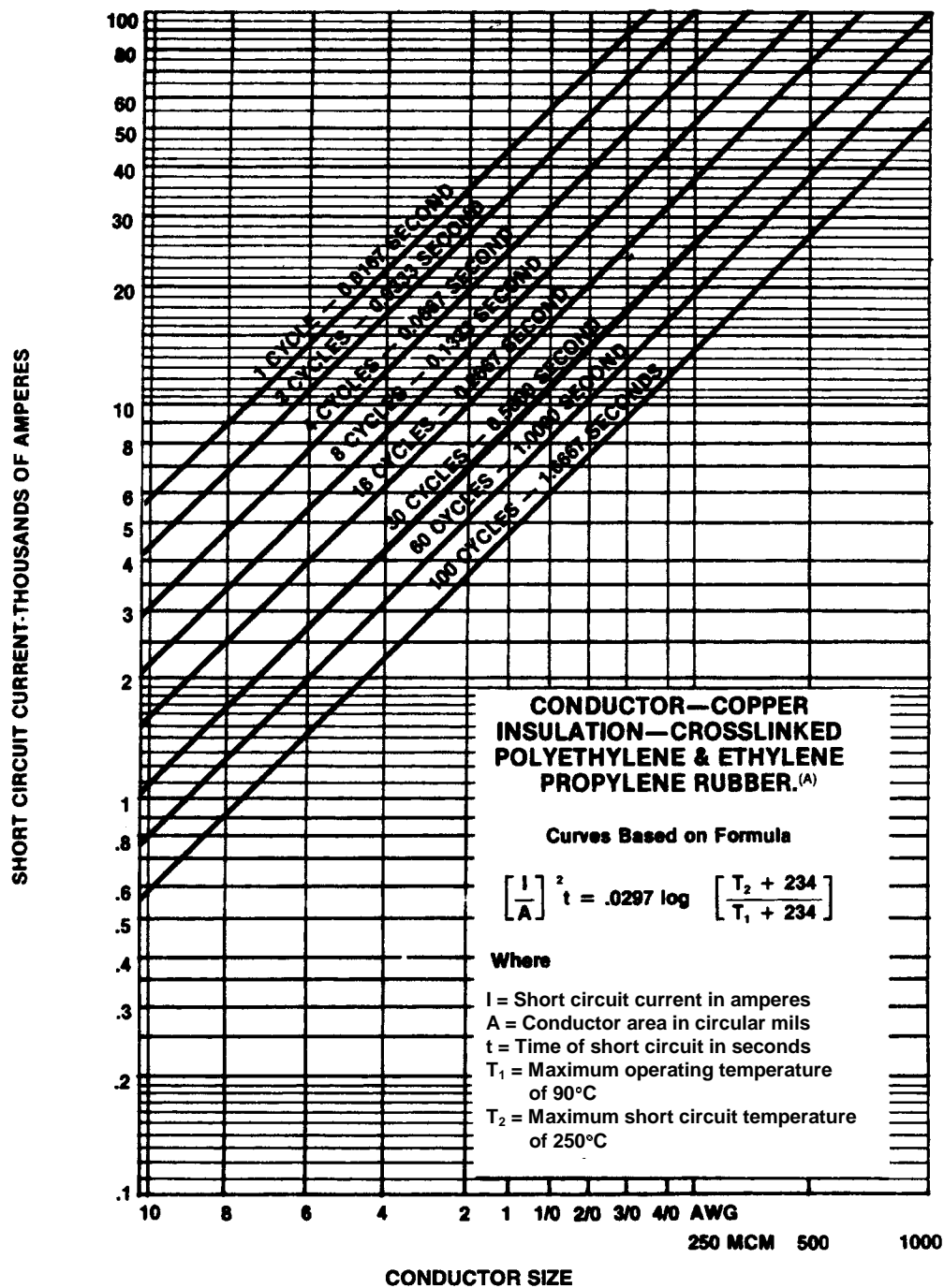


Figure 3 — Allowable short circuit currents for insulated copper conductors.

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^(A) To calculate this formula using metric units, change A to metric values as indicated in Table A1, Appendix A.

Table 2: Average Impedance for Various Conductor Sizes^(A)

Conductor^(B)	Average 60-Hz Impedance (Ohms/1,000 ft)	Average 60-Hz Impedance (Ohms/km)
#6 AWG	0.923	3.03
#2 AWG	0.366	1.20
#1/0 AWG	0.2295	0.753
#4/0 AWG	0.1097	0.360
250 MCM	0.0968	0.318
500 MCM	0.0492	0.161
1,000 MCM	0.0259	0.0850
2,000 MCM	0.0151	0.0495
4,000 MCM	0.00972	0.0319

^(A) Fusing current is 10% higher than current for 684°C (1,232°F) temperature rise.

^(B) For cable sizes in metric units, see Appendix A.

sized shunting circuit should be provided to permit isolation of the grounding device during testing or maintenance.

4.11.2 Certain types of sealed, explosion-proof, enclosed, or self-healing lightning arresters may be used in locations where a combustible atmosphere is anticipated, but only if it can be determined that the maximum possible power fault current does not exceed the design rating of the arrester. Open spark gaps shall not be used in these locations.

4.12 Stray Direct Current Areas

4.12.1 In areas where stray direct currents are present, galvanic anodes (including those in

electrolytic grounding cells), grounding grids, or grounds directly connected to the structure may pick up stray direct current. This current could possibly discharge directly to earth from the structure at other locations, resulting in corrosion of the structure at those points. Also, direct current pickup by the structure could lead to direct current discharge to earth through the galvanic anodes or grounding devices, resulting in increased consumption of the anode material or corrosion of grounding rods and an increase in their effective resistance to earth. The use of DC decoupling devices should be considered in these cases.

Section 5: Personnel Protection

5.1 Introduction

5.1.1 This section recommends practices that contribute to the safety of people who, during construction, system operation, corrosion survey, or cathodic protection maintenance of metallic structures, may be exposed to the hazards of AC potentials on those structures. The possibility of hazards to personnel during construction and system operation because of contact with metallic structures exposed to AC electrical and/or lightning effects must be recognized and provisions made to alleviate such hazards. The severity of the personnel hazard is usually proportional to the magnitude of the potential difference between the structure and the earth or between separate structures. The severity also depends on the duration of the exposure. Before construction work is started, coordination with the appropriate utilities in the area must be made so that proper work procedures are established and the

construction does not damage or interfere with other utilities' equipment or operations.⁽⁴⁾

5.1.2 Each utility should be aware of the others' facilities and cooperate in the mitigation of the electrical effects of one installation on the other. The mitigation required for a specific situation must be based on safety considerations with good engineering judgment.

5.1.3 Increasing the separation distance between facilities is generally effective in reducing the electrical effects of one installation on another.

5.2 Recognition of Shock Hazards to Personnel

5.2.1 AC potentials on structures must be reduced to and maintained at safe levels to prevent shock hazards to personnel. The degree of shock hazard and the threshold levels of current that can be

⁽⁴⁾ In some cases, the electric utility can shut down the electrical transmission facility or block the reclosing features. The utility may designate a coordinator while the project is in progress. These possibilities should be explored with the electric utility.

tolerated by human beings depend on many factors. The possibility of shock from lower voltages is the most difficult to assess. The degree of shock hazard depends on factors such as the voltage level and duration of human exposure, human body and skin conditions, and the path and magnitude of any current conducted by the human body. The magnitude of current conducted by the human body is a function of the internal impedance of the voltage source, the voltage impressed across the human body, and the electrical resistance of the body path. This resistance also depends on the contact resistance (e.g., wet or dry skin, standing on dry land

or in water) and on the current path through the body (e.g., hand-to-foot, hand-to-hand, etc.).

5.2.1.1 The safe limits must be determined by qualified personnel based on anticipated exposure conditions. For the purpose of this standard, 15 V AC (rms) open circuit or a source current capacity of 5 mA or more are considered to constitute an anticipated shock hazard. Tables 3 and 4 indicate the probable human resistance to electrical current and current values affecting human beings.

TABLE 3: Human Resistance to Electrical Current^(A)

Dry skin	100,000 to 600,000 ohms
Wet skin	1,000 ohms
Internal body—hand to foot	400 to 600 ohms
Ear to ear	(about) 100 ohms

^(A) Reprinted with permission from the National Safety Council. *Accident Prevention Manual for Business & Industry: Engineering & Technology*, 10th ed. Itasca, IL: National Safety Council, 1992.

TABLE 4: 60-Hz Alternating Current Values Affecting Human Beings

Current	Effects
1 mA or less	No sensation—Not felt.
1 to 8 mA	Sensation of shock—Not painful; individual can let go at will; muscular control not lost.
8 to 15 mA	Painful shock—Individual can let go at will; muscular control not lost.
15 to 20 mA	Painful shock—Muscular control lost; cannot let go.
20 to 50 mA	Painful shock—Severe muscular contractions; breathing difficult.
50 to 100 mA (possible)	Ventricular fibrillation—Death will result if prompt cardiac massage not administered.
100 to 200 mA (certain)	Defibrillator shock must be applied to restore normal heartbeat. Breathing probably stopped.
200 mA and over	Severe burns—Severe muscular contractions; chest muscles clamp heart and stop it during shock (ventricular fibrillation if prevented). Breathing stopped—heart may start following shock, or cardiac massage may be required.

Source: Unknown

5.2.1.2 In areas (such as urban residential zones or school zones) where a high probability exists that children (who are more sensitive to shock hazard than are adults) can come in contact with a structure under the influence of induced AC voltage, a lower voltage shall be considered.

5.2.1.3 The beginning sensation of shock, which may occur at 1 to 8 mA, may not be painful or harmful to a human being but may lead to an accident by causing rapid involuntary movement of a person.

5.2.2 In areas of AC influence, any measured AC voltages between a structure and ground (or some other adjacent structure) shall be considered an indication that further study is required.

5.2.3 When the voltage level on a structure presents a shock hazard, the voltage level must be reduced to safe levels by taking remedial measures. In those cases in which the voltage level cannot be reduced to a safe level on aboveground appurtenances, other safety measures shall be practiced to prevent shock to operating and maintenance personnel and to the public (see Paragraph 4.3).

5.3 Construction

5.3.1 Severe hazards may exist during construction of facilities adjacent to AC power systems. A responsible person shall be in charge of electrical safety. This person shall be fully aware of proper grounding procedures and of the dangers associated with inductive and capacitive couplings, fault current, lightning, etc., on aboveground and underground

structures. The person must also know the hazards of the construction equipment being used as related to the "limit-of-the-approach" regulations governing them.⁶ The person shall be furnished with the instrumentation, equipment, and authority required to implement and maintain safe working conditions.

5.3.2 The AC potential difference between a structure and the earth can be substantially reduced by appropriate grounding procedures. The AC potential difference between structures can be reduced by appropriate bonding procedures. The AC potential difference between separate points in the earth can be reduced through the use of appropriate grounding grids. The grounding or bonding procedure for safe construction activities depends upon the type, magnitude, and duration of the AC exposure. Each situation shall be analyzed by a competent person, and safe operating procedures shall be employed during the entire construction operation.

5.3.3 During the construction of metallic structures in areas of AC influence, the following minimum protective requirements are prescribed:

(a) On long, metallic structures paralleling AC power systems, temporary electrical grounds shall be used at intervals not greater than 300 m (1,000 ft), with the first ground installed at the beginning of the section. Under certain conditions, a ground may be required on individual structure joints or sections before handling.

(b) All temporary grounding connections shall be left in place until immediately prior to backfilling. Sufficient temporary grounds shall be maintained on each portion of the structure until adequate permanent grounding connections have been made.

5.3.4 Temporary grounding connections may be made to ground rods, bare pipe casing, or other appropriate grounds. These temporary grounding facilities are intended to reduce AC potentials. Direct connections made to the electrical utility's grounding system during construction could increase the probability of a hazard during switching surges, lightning strikes, or fault conditions, and may intensify normal steady state effects if the grounding system is carrying AC; such connections should be avoided when possible.

5.3.5 Cables used for bonding or for connections to grounding facilities shall have good mechanical strength and adequate conductivity. As a minimum, copper conductor 35-mm² (0.054-in.²) (No. 2 AWG) stranded welding cable or equivalent is recommended. See Table 1 and Figures 1, 2, and 3

for cable sizes adequate to conduct the anticipated fault current safely.

5.3.6 Temporary cable connections to the affected structure and to the grounding facilities shall be securely made with clamps that apply firm pressure and have a current-carrying capacity equal to or greater than that of the grounding conductor. Clamps shall be installed so that they cannot be accidentally dislodged.

5.3.7 All permanent cable connections shall be thoroughly checked to ensure that they are mechanically and electrically sound and properly coated prior to backfilling.

5.3.8 The grounding cable shall first be attached to the grounding facilities and then securely attached to the affected structure. Removal shall be in reverse order. Properly insulated tools or electrical safety gloves shall also be used to minimize the shock hazards. **THE END CONNECTED TO THE GROUND SHALL BE REMOVED LAST.**

5.3.8.1 In those instances in which high power levels are anticipated in the bonding cable, the following procedure is recommended to prevent electrical arc burns or physical damage to the coating or metal on this pipe.

(a) The pipe grounding clamp shall be connected to the pipeline.

(b) The grounding cable shall be connected to the grounding facility.

(c) The grounding cable shall be connected to the grounding clamp on the structure.

5.3.9 All grounding attachments and removals shall be made by, or under the supervision of, the person in charge of electrical safety.

5.3.10 If hazardous AC potentials are measured across an isolating joint or flange, both sides of the joint or flange shall be grounded and/or bonded across. If required, a permanent bond shall be made before the temporary bond is removed.

5.3.11 Before the temporary grounding facilities are removed, provisions must be made to permanently control the effects of AC potentials on the affected structure. These provisions depend on the type of cathodic protection, the type of structure, and the anticipated magnitude of AC potentials.

5.3.12 Vehicles and other construction equipment are subject to existing electrical safety regulations when operated in the vicinity of high-voltage AC lines.⁶

5.3.12.1 Metallic construction sheds or trailers, fences, or other temporary structures shall be grounded if subject to AC influence.

5.3.13 The person in charge of electrical safety shall communicate at least daily with the utility controlling the involved power lines to ascertain any switching that might be expected during each work period. This person may request that reclosing procedures be suspended during construction hours, and may explore the possibility of taking the power line out of service. The person shall also keep informed of any electrical storm activity that might affect safety on the work site. The person shall order a discontinuation of construction during local electrical storms or when thunder is heard.

5.3.14 The use of electrically isolating materials for aboveground appurtenances such as vent pipes, conduits, and test boxes may reduce shock hazards in specific instances. However, electrical wires permanently attached to the pipeline, such as cathodic protection test wires, may have a high possibility of a shock hazard because they cannot be isolated from the pipe (see Paragraph 7.2.6).

5.4 Operations and Maintenance

5.4.1 Maintenance of structures and cathodic protection facilities under conditions that include AC potentials may require special precautions. Warning signs shall be used as a minimum precaution. All maintenance shall be performed by or under the supervision of a person familiar with the possible hazards involved. Personnel must be informed of these hazards and of the safety procedures to follow.

5.4.2 Testing of devices intended to limit AC potentials shall be in accordance with manufacturer's recommendations and performed under the supervision of a person familiar with the possible hazards involved. In those areas where the presence of combustible vapors is suspected, tests must be conducted before connections are made or broken to determine that the combustible vapor level is within safe limits. No more than one device intended to limit the AC potential should be disconnected at any

one time. When a single protective device is to be installed, a temporary shunt bond, with or without another decoupling device, must be established prior to removing the unit for service.

5.4.3 Testing of cathodic protection systems under the influence of AC potentials must be performed by or under the supervision of a qualified person. In all cases, tests to detect AC potentials shall be performed first, and the structure shall be treated as a live electrical conductor until proven otherwise. Cathodic protection records should include the results of these tests.

5.4.4 Test stations for cathodic protection systems on structures that may be subject to AC potentials shall have dead-front construction to reduce the possibility of contacting energized test leads. Test stations employing metallic pipes for support must be of dead-front construction.

5.4.5 Safe work practices must include attaching all test leads to the instruments first and then to the structure to be tested. Leads must be removed from the structure first and from the instruments last.

5.4.6 When structures subject to AC influence are exposed for the purpose of cutting, tapping, or separating, tests shall be made to determine AC potentials or current to ground. In the event that potentials or currents greater than those permitted by Paragraph 5.2 are found, appropriate remedial measures shall be taken to reduce the AC effects to a safe level. In the event this cannot be achieved, the structure shall be regarded as a live electrical conductor and treated accordingly. Solid bonding across the point to be cut or the section to be removed shall be established prior to separation, using as a minimum the cable and clamps outlined in Paragraphs 5.3.5 and 5.3.6.

5.4.7 On facilities carrying combustible liquids or gases, safe operating procedures require that bonding across the sections to be separated precede structure separation, regardless of the presence of AC.

Section 6: AC and Corrosion Control Considerations

6.1 Introduction

6.1.1 This section recommends practices for determining the level of AC influence and lightning effects to which an existing metallic structure may be subjected. This section also outlines several points for consideration regarding the effects these

potentials may have on corrosion control systems and associated equipment.

6.2 Determination of AC Influence and Lightning Effects

6.2.1 A cathodic protection system design should include an evaluation to estimate the level of AC

potentials and currents under normal conditions, fault conditions, and lightning surges. Because significant AC potentials may be encountered during field surveys, all personnel shall follow proper electrical safety procedures and treat the structure as a live electrical conductor until proven otherwise.

6.2.2 Tests and investigations to estimate the extent of AC influence should include the following:

- (a) Meeting with electric utility personnel to determine peak load conditions and maximum fault currents and to discuss test procedures to be used in the survey.
- (b) Electrical measurement of induced AC potentials between the affected structure and ground.
- (c) Electrical measurement of induced AC current on the structure.
- (d) Calculations of the potentials and currents to which the structure may be subjected under normal and fault conditions.⁸

6.2.3 A survey should be conducted over those portions of the affected structure where AC exposure has been noted or is suspected. The location and time that each measurement was taken should be recorded.

6.2.3.1 The potential survey should be conducted using a suitable AC voltmeter of proper range. Contact resistance of connections should be sufficiently low to preclude measurement errors because of the relationship between external circuit impedance and meter impedance. Suitable references for measurements are:

- (a) A metal rod.⁽⁵⁾
- (b) Bare pipeline casings, if adequately isolated from the carrier pipe.
- (c) Tower legs or power system neutrals, if in close proximity to the affected structure. (Meter connections made to tower legs or power system neutrals may present a hazard during switching surges, lightning strikes, or fault conditions.)

6.2.3.2 The presence of AC on a structure may be determined using a suitable AC voltmeter to

measure voltage (IR) drop at the line current test stations. This method, however, provides only an indication of current flow, and cannot be readily converted to amperes because of the AC impedance characteristics of ferromagnetic materials. A clamp-on AC ammeter may be used to measure current in temporary or permanent bond connections.

6.2.3.3 Indications of AC power levels on affected structures may be obtained by temporarily bonding the structure to an adequate ground and measuring the resulting current flow with a clamp-on AC ammeter while measuring the AC potential. Suitable temporary grounds may be obtained by bonding to tower legs, power system neutral, bare pipeline casings, or across an isolating joint to a well-grounded system. DC drainage bonds existing on the structure under investigation should also be checked for AC power levels.

6.2.3.4 Locations indicating maximum AC potential and current flow values during the survey discussed in Paragraphs 6.2.3 through 6.2.3.2 should be surveyed with recording instruments for a period of 24 hours or until the variation with power-line load levels has been established.⁽⁶⁾

6.2.4 In designing mitigative measures, the following power system parameters should be determined:

- (a) Maximum operating and emergency load conditions.
- (b) Maximum single line-to-ground fault current and duration.
- (c) Maximum phase-to-phase fault current and duration.
- (d) Type of grounding system used.

6.3 Special Considerations in Cathodic Protection Design

6.3.1 AC influence on the affected structure and its associated cathodic protection system should be considered.

6.3.2 Cathodic protection survey instruments should have sufficient AC rejection to provide accurate DC data.

⁽⁵⁾ Following meter hookup, the reference rod should be inserted deeper into the earth until no further potential increase is noted. This reduces the possibility of high-resistance contact errors in the measurement.

⁽⁶⁾ Survey data gathered in accordance with Paragraphs 6.2.3 through 6.2.3.4 should be reviewed with electric utility personnel for the purpose of correlating with the power-line operating conditions at the time of the survey.

6.3.3 The AC current in the structure to be protected may flow to ground through cathodic protection equipment. Current flowing in the cathodic protection circuits under normal AC power system operating conditions may cause sufficient heating to damage or destroy the equipment. Heating may be significantly reduced by the use of properly designed series inductive reactances and/or shunt capacitive reactances in the cathodic protection circuits.

6.3.3.1 Rectifiers should be equipped with lightning and surge protection at the AC input and DC output connections.

6.3.3.2 Resistance bonds for the purpose of DC interference mitigation should be designed for the maximum normal AC and DC current flow in order to prevent damage to the bond. Installation of polarization cells or other devices

in parallel with DC resistance bonds may prevent damage to bonds. Installation of semiconductors in DC interference bonds between cathodically protected structures may result in undesirable rectification.

6.3.3.3 When bonds to other structures or grounds are used, polarization cells or grounding cells should be used, as required, in order to maintain effective levels of cathodic protection.

6.3.3.4 Semiconductor drain switches for the mitigation of stray DC from traction systems should be provided with surge current protection devices.

6.3.4 In DC stray current areas, the grounding methods should be chosen to avoid creating interference problems.

Section 7: Special Considerations in Operation and Maintenance of Cathodic Protection and Safety Systems

7.1 Introduction

7.1.1 This section outlines safe maintenance and testing procedures for cathodic protection systems on structures subject to AC influence.

7.2 Safety Measures for Operation and Maintenance of Cathodic Protection Systems

7.2.1 Cathodic protection rectifiers that are subject to damage by adjacent electric utility systems should be checked for proper operation at more frequent intervals than rectifiers not subject to electric system influence.

7.2.2 Cathodic protection testing or work of similar nature must not be performed on a structure subject to influence by an adjacent electric utility system during a period of thunderstorm activity in the area.

7.2.3 When repeated rectifier outages can be attributed to adjacent electric utility system influences, positive measures must be taken to maintain continuous rectifier operation. One or more of the following mitigative measures may be employed:

(a) Self-healing lightning arresters across the AC input and DC output terminals.

(b) Heavy-duty choke coils installed in the AC and/or DC leads.

7.2.4 If galvanic anodes are used for cathodic protection in an area of AC influence and if test stations are available, the following tests should be conducted during each structure survey using suitable instrumentation:

(a) Measure and record both the AC and DC currents from the anodes.

(b) Measure and record both the AC and DC structure-to-electrolyte potentials.

7.2.5 At all aboveground pipeline metallic appurtenances, devices used to keep the general public or livestock from coming into direct contact with the structure shall be examined for effectiveness. If the devices are found to be ineffective, they shall be replaced or repaired immediately.

7.2.6 In making test connections for electrical measurements, all test leads, clips, and terminals must be properly insulated. Leads shall be connected to the test instruments before making connections to the structure. When each test is completed, the connections shall be removed from the structure before removing the lead connection from the instrument. All test connections must be made on a step-by-step basis, one at a time.

7.2.7 When long test leads are laid out near a power line, significant potentials may be induced in these leads. The hazards associated with this situation may be reduced by using the following procedures:

(a) Properly insulate all test lead clips, terminals, and wires.

(b) Avoid direct contact with bare test lead terminals.

(c) Place the reference electrodes in position for measurement prior to making any test connections.

(d) Connect the lead to the reference electrode and reel the wire back to the test location.

(e) Connect the other test lead to the instrument and then to the structure.

(f) Connect the reference electrode lead to the instrument.

(g) When the tests are complete, disconnect in reverse order. NOTE: Close-interval pipe-to-electrolyte surveys using long lead wires require special procedures and precautions.

7.2.8 Tools, instruments, or other implements shall not be handed at any time between a person

standing over a ground mat or grounding grid and a person who is not over the mat or grid.

7.2.9 Grounding facilities for the purpose of mitigating AC effects should be carefully tested at regular intervals to ascertain the integrity of the grounding system.

7.2.9.1 No disconnection or reconnection shall be allowed when a flammable or explosive atmosphere is suspected without first testing to ensure a safe atmosphere.

7.2.9.2 No one shall make contact with the structure, either directly or through a test wire, while a grounding grid is disconnected for test purposes.

7.2.9.3 Measurement of the resistance to earth of disconnected grounds shall be made promptly to minimize personnel hazards.

7.2.10 All interference mitigation devices and test equipment should be maintained in accordance with the manufacturer's instructions.

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⁽⁷⁾ The Institute of Radio Engineers (IRE) and the American Institute of Electrical Engineers (AIEE) merged in 1963 to form the Institute of Electrical and Electronics Engineers (IEEE).

⁽⁸⁾ National Fire Protection Agency (NFPA), 1 Batterymarch Park, P.O. Box 9101, Quincy, MA 02269-9101.

⁽⁹⁾ American National Standards Institute (ANSI), 11 W 42nd St., New York, NY 10036.

⁽¹⁰⁾ Occupational Safety and Health Administration (OSHA), 200 Constitution Ave. NW, Washington, DC 20210.

⁽¹¹⁾ American Gas Association (AGA), 1515 Wilson Blvd., Arlington, VA 22209.

⁽¹²⁾ Electric Power Research Institute (EPRI), 3412 Hillview Ave., Palo Alto, CA 94304-1395.

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Appendix A: Wire Gauge Conversions

Table A1 provides the nearest metric size for the conductor sizes mentioned in this standard.

Table A1: Wire Gauge Conversions

Conductor Size	Diameter in mils	Nearest metric size (mm ²)	Diameter in mm of nearest metric size
4,000 MCM	2,000	2,000	50.5
2,000 MCM	1,410	1,000	35.7
1,000 MCM	1,000	500	25.2
500 MCM	707	240	17.5
250 MCM	500	120	12.4
4/0 AWG	460	120	12.4
3/0 AWG	410	80	10.04
2/0 AWG	365	70	9.44
1/0 AWG	325	50	7.98
1 AWG	290	50	7.98
2 AWG	258	35	6.68
4 AWG	204	25	5.64
6 AWG	162	16	4.51
8 AWG	128	10	3.57
10 AWG	102	6	2.76

Source: Fink and Carroll, Standard Handbook for Electrical Engineers, 10th ed. (New York, NY: McGraw-Hill, 1968).

⁽¹³⁾ Canadian Gas Association (CGA), 20 Eglinton Avenue West, Suite 1305, P.O. Box 2017, Toronto, ON M4R 1K8 CANADA.

Standard Recommended Practice

Internal Cathodic Protection Systems in Oil-Treating Vessels

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Reaffirmed 2001-09-20
Approved October 1975
Revised March 1995
NACE International
1440 South Creek Drive
Houston, TX 77084-4906
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ISBN 1-57590-135-8
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Foreword

This standard recommended practice is a general guide for the application of effective cathodic protection to all oil-treating vessels. This standard covers design criteria, the selection and installation of applicable systems, and the operation, monitoring, and maintenance of installed systems. There are many design variations in existing oil-treating vessels, with new designs being introduced continually. The preparation of a recommended practice for the cathodic protection of each individual vessel design is not practical. Therefore, this standard is not specific with respect to one or more vessel designs. It is intended for use by corrosion engineers involved in oil and gas production, especially those concerned with surface facilities. Nothing contained in this standard is intended to conflict with applicable codes, including OSHA⁽¹⁾ regulations.

This standard was originally prepared in 1975 by Task Group T-1E-6, a component of Unit Committee T-1E on Cathodic Protection of Oilfield Equipment, and revised in 1995 by Task Group T-1E-11. It was reaffirmed in 2001 by Specific Technology Group (STG) 35 on Pipelines, Tanks, and Well Casings. This STG is composed of corrosion consultants, corrosion engineers from oil- and gas-producing companies, representatives from manufacturers, and others concerned with internal corrosion control in oil-treating vessels.

In NACE standards, the terms *shall*, *must*, *should*, and *may* are used in accordance with the definitions of these terms in the *NACE Publications Style Manual*, 4th ed., Paragraph 7.4.1.9. *Shall* and *must* are used to state mandatory requirements. *Should* is used to state something considered good and is recommended but is not mandatory. *May* is used to state something considered optional.

⁽¹⁾ Occupational Safety and Health Administration (OSHA), 200 Constitution Ave. NW, Washington, DC 20210.

**NACE International
Standard
Recommended Practice**

**Internal Cathodic Protection Systems
in Oil-Treating Vessels**

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Section 1: General

1.1 This standard presents recommended practices for the cathodic protection of internal surfaces of oil-treating vessels, heat exchangers, or the water side of process vessels.

1.2 The provisions of this standard should be applied under the direction of a corrosion engineer. The term "corrosion engineer," as used in this standard, refers to a person who, by reason of knowledge of the physical sciences and the principles of engineering and mathematics, acquired by professional education and related practical experience, is qualified to engage in the practice of corrosion control in oil-treating vessels.

1.3 Effective performance of the cathodic protection system requires operation within the limits of the design, monitoring of the system, and maintenance to replace damaged and consumed parts.

1.4 Cathodic protection is not effective when applied to steel surfaces in the oil or gas phase because of the absence of an electrolyte. Coatings and/or chemical inhibitors should be used to control corrosion on the steel surfaces in the oil and gas phase.

Section 2: Definitions

Anode: The electrode of an electrochemical cell at which oxidation occurs. Electrons flow away from the anode in the external circuit. Corrosion usually occurs and metal ions enter the solution at the anode.

Cathode: The electrode of an electrochemical cell at which reduction is the principal reaction. Electrons flow toward the cathode in the external circuit.

Cathodic Protection: A technique to reduce the corrosion of a metal surface by making that surface the cathode of an electrochemical cell.

Coating: A liquid, liquefiable, or mastic composition that, after application to a surface, is converted into a solid protective, decorative, or functional adherent film.

Corrosion: The deterioration of a material, usually a metal, that results from a reaction with its environment.

Corrosion Engineer: A person, who by reason of knowledge of the physical sciences and the principles of engineering and mathematics, acquired by professional education and related practical experience, is qualified to engage in the practice of corrosion control.

Current Density: The current to or from a unit area of an electrode surface.

Driving Potential: Difference in potential between the anode and the steel structure.

Electrode: A conductor used to establish contact with an electrolyte and through which current is transferred to or from an electrolyte.

Electrolyte: A chemical substance containing ions that migrate in an electric field. For the purpose of this standard,

electrolyte refers to the water, including the chemicals contained therein, adjacent to and in contact with a submerged metal surface.

Galvanic Anode: A metal that provides sacrificial protection to another metal that is more noble when electrically coupled in an electrolyte. This type of anode is the electron source in one type of cathodic protection.

Holiday: A discontinuity in a protective coating that exposes unprotected surface to the environment.

Impressed Current: An electric current supplied by a device employing a power source that is external to the electrode system. (An example is direct current for cathodic protection.)

Passivation: A reduction of the anodic reaction rate of an electrode involved in corrosion.

Polarization: The change from the open-circuit potential as a result of current across the electrode/electrolyte interface.

Reference Electrode: An electrode whose open-circuit potential is constant under similar conditions of measurement, which is used for measuring the relative potentials of other electrodes.

Salt Bridge: A salt solution used with a reference electrode to bridge a gap in an electrical circuit to obtain potential data with a reference electrode.

Steel-to-Water Potential: The potential difference between a steel vessel surface and a reference electrode immersed in the water with which the steel vessel surface is in contact (sometimes referred to as cathodic solution potential).

Section 3: Determination of Need for Cathodic Protection

3.1 General

3.1.1 Experience reveals that corrosion and metal loss is to be expected in any oil-treating vessel where any portion of the internal steel surface is exposed to oilfield brines because of their aggressive corrosive nature. The need for cathodic protection is contingent on the severity of existing or anticipated corrosion and the extent to which it affects equipment operation. Consistent with the latter, cathodic protection should be installed when it will accomplish one or more of the following: remove or minimize unsafe conditions caused by failure, provide economical control over equipment failures and losses, and remove or minimize the possibility of vessel content loss because of leaks or vessel collapse.

3.1.2 Internal coatings may be used in conjunction with cathodic protection to protect oil-treating vessels. Internal coating reduces the surface area of steel to be protected.

3.2 Corrosion Rates

3.2.1 The corrosiveness of a fluid stream is a function of the following:

3.2.1.1 Corrosion usually becomes more severe as the conductivity (dissolved solids content) of water (electrolyte) increases, but low-conductivity water can be corrosive.

3.2.1.2 Corrosion in produced oilfield brines usually increases as the partial pressure of acid-forming components, such as carbon dioxide (CO₂) or hydrogen sulfide (H₂S), increases.

3.2.1.3 Corrosion is accelerated by even trace amounts of oxygen.

3.2.1.4 Corrosion usually increases with increasing temperature unless scaling is increased.

3.2.1.5 Corrosion usually increases with increasing flow velocity and turbulence.

Section 4: Design and Selection of Cathodic Protection System

4.1 Basic Design Criteria

4.1.1 The design of a vessel's cathodic protection system depends on the internal configuration of the vessel. Selection of the appropriate system depends on factors such as initial cost, maintenance, type and condition of coatings (if any), power availability and cost, and system life.

4.1.2 Vertical cylindrical vessels containing no baffles, compartments, firetubes, etc., are usually protected with anodes or strings of anodes suspended from the deck (roof) of the vessel. This design method offers two advantages over other designs: (1) better current distribution because anodes are parallel to the vessel walls, and (2) deteriorated or depleted anodes can be replaced without lowering the water level or draining the vessel.

4.1.3 Compartmented vessels or those containing baffles, firetubes, spreaders, etc., should have at least one anode installed in each compartment exposed to the corrosive fluid. If a vessel is not designed to accommodate a cathodic protection system that will provide effective protection throughout, it may be necessary to make modifications or redesign the vessel interior to provide access to areas needing cathodic protection by installing fittings in the vessel for

inserting anodes through the walls. An example of such modification is positioning of a spreader in a heater treater below the firetubes so there is sufficient clearance to install an anode between the firetube and spreader.

4.1.4 Correct location and position of anodes in vessels are essential for proper current distribution. Cathodic protection anodes should be placed such that their protective current can be distributed to all surfaces exposed to the corrosive electrolyte. Each anode should be located as near to the center of the compartment or center of the electrolyte as practical.

4.1.5 Factors determining the number, weight, and shape of anodes required for cathodic protection of vessels are:

- (a) area of bare water-immersed steel to be protected;
- (b) current density required;
- (c) anticipated current output of the anodes;
- (d) vessel configuration; and
- (e) desired life of the cathodic protection system.

4.1.6 Current density requirements can range from 50 to 400 mA/m² (5 to 40 mA/ft²) of bare water-immersed steel. In the absence of specific current density data, 100 mA/m² (10 mA/ft²) is commonly used for design. However, vessels handling water containing depolarizers, such as H₂S and oxygen, or operating at high temperatures and/or high flow rates, could require higher current densities to maintain protective potentials. Internal coating of vessels decreases the area of bare steel in contact with water and reduces the amount of current required for corrosion protection.

4.2 System Selection

4.2.1 Cathodic protection can be provided by impressed current systems or galvanic anode systems. Typical performance data for commonly used impressed current and galvanic anodes are shown in Table 1. Prior to the application of either impressed current or galvanic anodes, it must be ensured that treated electrolytes are chemically compatible with the anode.

Table 1—Typical Performance Data for Commonly Used Impressed Current and Galvanic Anodes

Type of Anode	A-h/kg ^(A)	A-h/lb ^(A)
<u>Impressed Current Anodes</u>		
Linseed oil-impregnated graphite	13,000 to 15,000 (14,000)	6,000 to 7,000 (6,500)
High-silicon cast iron with chromium	18,000 to 24,000 (19,000)	8,000 to 11,000 (8,500)
<u>Galvanic Anodes</u>		
Magnesium	1,000 to 1,100 (1,000)	450 to 500 (450)
Aluminum ^(B)	400 to 2,000 (1,300)	200 to 950 (600)
Zinc	700 to 800 (800)	300 to 350 (350)

^(A) Values in parentheses are commonly used in design calculations.

^(B) Caution: The performance and efficiency of aluminum anodes vary with the alloy, and with certain alloys they vary with the heat treatment.

Note: Anode efficiencies vary widely, particularly for galvanic anodes. Factors influencing this include anode locations, position and surface area, water composition and temperature, and selective electrochemical attack.

4.2.2 Impressed current systems have greater flexibility if high current demand is anticipated.

4.2.2.1 Impressed current systems can be used in any water, but are usually the most practical in high-resistivity waters where an appreciable amount of current is required to achieve protection.

4.2.2.2 Impressed current systems typically require more monitoring and maintenance than galvanic anodes.

4.2.2.3 Automatic potential rectifier systems decrease the likelihood of underprotection or the excessive use of power and coating disbondment resulting from overprotection (see Paragraph 4.3.2).

4.2.2.4 Impressed current anodes should be provided with individual lead wires to the rectifier for control and measurement of current output from each individual anode.

4.2.3 Galvanic anodes are commonly used when electrical power is not feasible to use or is not available and may be preferred for low-current-requirement installations, even if electrical power is available. The effects of the produced fluid chemistry on the performance of a galvanic anode should be considered. The pH of produced fluids containing dissolved CO₂ and/or H₂S can be lowered to acidic levels that can attack zinc, aluminum, or magnesium. Large concentrations of H₂S may also react with the anode to alter its performance. The possibility of the presence of other impurities, such as amines, emulsions, or even small quantities of mercury, should be considered. Consideration should be given to effects of the various oilfield treating chemicals and workover fluids that may flow through the vessel being protected. Residual acids from stimulation treatments may cause severe attack on all galvanic anodes. The potential effects of demulsifiers, scale and corrosion inhibitors, drilling mud, and other material that might be added to production should be considered.

4.2.4 Galvanic anode materials most commonly used are aluminum, magnesium, and zinc alloys. The

composition, resistivity, and temperature of the electrolyte largely dictate which material is most suitable.

4.2.4.1 Aluminum alloys are commonly used in brines with resistivities below 100 ohm-cm. Aluminum's lower driving potential, compared with that of magnesium, leads to lower current output and longer life. Generally, more than one aluminum anode is required to provide current output equivalent to that of magnesium.

4.2.4.1.1 Consideration must be given to selection of the proper aluminum alloy (pure aluminum should not be used as an anode) to ensure adequate protection at optimum economy. The electrochemical properties (potential and current capacity) of aluminum anodes are dependent on the alloy, the electrolyte composition, and the electrolyte temperature. Temperatures above 49°C (120°F) can reduce the current capacity of aluminum anodes.

4.2.4.2 Magnesium alloys are commonly used in brines with resistivities above 100 ohm-cm. Magnesium's higher driving potential, compared with that of aluminum, leads to higher current output and shorter life. If magnesium anodes are used in low-resistivity electrolytes, current output should be controlled by resistors in the external circuits.

4.2.4.3 Zinc alloys are not commonly used in vessels because they may show a decrease in potential with increase in electrolyte temperature and may possibly become cathodic to steel at temperatures in the range of 54°C (130°F).

4.3 Internally Coated Vessels

4.3.1 Cathodic protection mitigates corrosion at coating holidays.

4.3.2 Excessive cathodic protection potentials may cause coating damage. Generally, at polarized potentials more negative than -1.05 to -1.10 V (copper/copper sulfate reference electrode [CSE]), excessive hydrogen can be formed and cause coating damage.

Section 5: Anode Installation

5.1 Vertical Suspension

5.1.1 Anodes must be spaced to distribute current uniformly to the vessel walls and bottom, and at a depth that assures that some anodes are submerged regardless of water level. Either type of anode (galvanic or impressed current) can be installed in this manner.

5.1.2 Impressed current anodes must be suspended from a suitable hanger (deck mount), properly isolated to prevent grounding of the lead wire to the vessel.

5.1.3 Galvanic anodes should be electrically isolated where current monitoring is contemplated.

5.2 Internally Supported

5.2.1 Galvanic anodes may be placed on supports on the vessel floor and isolated from the vessel. Anode leads can be brought out through watertight connections welded in the clean-out plate and connected back to the vessel wall. Shunts and resistors may then be installed in the external anode leads to monitor or regulate anode performance.

5.2.2 Alternatively, galvanic anodes may be bolted or welded to brackets permanently affixed to the vessel surface. However, this type of installation does not

allow any method for monitoring the anode output or knowledge of anode consumption other than by visual inspection.

5.3 Vessel Wall Placement

5.3.1 Galvanic or impressed current anodes can be installed horizontally in compartmented vessels through mountings welded into the side of the vessel.

5.3.2 Anode heads for installation in nipples are most commonly made of a nonmetallic material designed to withstand the temperature and pressure within the vessel. The shield portion of the head must be of sufficient length to prevent anode grounding to the vessel or excessive current discharge close to the anode entrance port. In all cases, actual lengths of the nipple and the anode head, as well as the positioning of the nipple on the curved surfaces, must be related in design in order to prevent this undesired current discharge. Anode entrance ports should be installed during fabrication of vessels. Materials and welding procedures should be consistent with primary vessel design.

5.3.3 When steel anode mounting heads are considered, they must be properly designed to provide isolation between the anode mounting head and the vessel.

Section 6: Reference Electrode Entrance

6.1 Methods

6.1.1 Entrance ports for insertion of reference electrodes should be installed in the vessel at the same time as the anode entrance ports.

6.1.2 In compartmented vessels, reference electrode ports must be installed as far from the anodes as possible in order to obtain potentials representative of the steel surface. These ports are usually 2.5-cm (1-

in.) diameter connections welded into the vessel wall in each compartment and equipped with a 2.5-cm (1-in.) full-opening valve so that the reference electrode may be inserted into the vessel.

6.1.3 In vertical cylindrical vessels equipped with roof-type hatches, the reference electrode may be inserted through the hatches. If this is anticipated, the anodes should be installed at the maximum distance from the hatch.

Section 7: Criteria for Protection

7.1 Steel-to-Water Potential

7.1.1 The presence of a protective potential should be verified after the vessel is polarized. Polarization normally occurs within two weeks in bare vessels and within a few minutes in coated vessels.

7.1.2 The steel surface is protected if the surface is more negative than -0.85 V vs a CSE (-0.80 V vs a Ag/AgCl electrode). However, if the fluid contains sulfides/H₂S, a protection potential of -0.95 V vs a CSE (-0.90 V vs a Ag/AgCl electrode) is required to achieve

protection. Polarization and protection of the vessel are generally assured if the potential immediately after switching the cathodic protection current off is equal to or more negative than these values.

7.2 Coupon Tests

7.2.1 Coupons may be installed to monitor the effectiveness of cathodic protection. Coupons must be electrically connected to the vessel wall. Coupon weight-loss measurements are used to determine the effectiveness of protection.

Section 8: Monitoring, Records, and Maintenance

8.1 Monitoring

8.1.1 Operating personnel should visually inspect surfaces under cathodic protection whenever vessels are opened. In addition, thickness measurements of vessel walls should be taken to determine cathodic protection effectiveness.

8.1.2 Potential and/or anode current output surveys should be made monthly after initial installation of cathodic protection equipment until current requirements are established. After current requirements are established, quarterly surveys are usually adequate.

8.1.2.1 Care must be taken in placing the reference electrode into the treating vessel. For potential measurements, the electrode must be as far from the anodes as possible. In pressure vessels, the electrode is "inserted" (introduced into the vessel against existing vessel pressure) through a full-opening valve installed in the vessel for that purpose (see Paragraph 6.1.2). Reference electrodes manufactured to withstand pressure

and temperature can also be permanently installed.

8.1.2.2 Contamination of the reference electrode with oil or sediments such as iron sulfide must be avoided. A salt bridge may be used to prevent contamination of the reference electrode.¹

8.1.2.3 Location of the reference cell near an anode may indicate a higher potential than elsewhere in the vessel.

8.1.2.4 Water levels lower than normal may result in higher potentials because of increased current density.

8.1.3 Galvanic anodes are sometimes installed without shunts. However, if the cathodic protection system cannot be monitored by potential measurements, shunts of known resistance (normally 0.01 ohm) should be installed. Current measurements can be obtained by measurement of the potential across the shunt of known resistance.

8.2 Records

8.2.1 Record keeping is vital to effective maintenance of cathodic protection systems (and thus continued protection of the vessels).

8.2.2 Monthly records should be kept for all impressed current anode installations. The records should show DC voltage and amperage readings for each anode.

8.2.3 Quarterly records should be kept for galvanic anode installations. The records should show current readings on galvanic anodes.

8.3 Maintenance

8.3.1 Malfunctions should be repaired promptly to ensure desired performance. Corrosion damage can occur whenever the potentials are less negative than the values indicated in Paragraph 7.1.2.

8.3.2 Anodes must be replaced periodically as they are consumed. Zero current readings usually indicate deteriorated anodes, broken anode cables, malfunctioning rheostats, or loose connections in the circuit. Low current readings in galvanic systems may indicate similar problems.

8.3.3 Zero reported voltage or current readings may occur because of various malfunctions. A rectifier troubleshooting guide should be consulted when such malfunctions occur.

8.3.4 During maintenance of the vessel, visual examination of the vessel surfaces should be conducted to verify the effectiveness of the cathodic protection system. Deterioration of the surface of the vessel and/or interior welds indicates the need for relocation of the anodes, increasing quantity of anodes, or an appraisal of the cathodic protection system.

Section 9: Safety

9.1 Precautions must be taken to avoid sparks in the presence of flammable substances and explosive gas mixtures that may be present around oil-treating vessels.

9.2 The cable-to-anode connections in impressed current systems shall never be disconnected, nor shall the anode be removed, while the rectifier is in operation.

9.3 Usual precautions to prevent fire or explosion must be taken before a cathodic protection system can be installed or repaired in a vessel handling water mixed with oil or gas.

9.4 CAUTION: Usual precautions must be taken when monitoring or performing maintenance on cathodic protection systems in vessels containing H₂S. If the anodes in such vessels are to be removed for replacement or inspection, a mask approved for use in H₂S environments must be worn. Additional information on the toxicity of H₂S

can be obtained from the Manufacturing Chemists' Association's⁽²⁾ "Chemical Safety Data Sheet SD-36,"² and from *Dangerous Properties of Industrial Materials*.³

9.5 The rectifier case, external AC disconnect switch box, and any related metallic equipment must be grounded.

9.6 Depending on the area classification, explosion-proof rectifiers and electrical devices may be required.

9.7 Special gaskets capable of withstanding high temperatures should be used to mount anodes in fired vessels, particularly if the gaskets are located near the fire tubes.

9.8 Equipment, wiring, enclosures, and installation of cathodic protection systems must comply with all applicable codes, including OSHA regulations.

References

1. NACE Publication 35201 (latest revision), "Report on the Application and Interpretation of Data from External Coupons Used in the Evaluation of Cathodically Protected Metallic Structures" (Houston, TX: NACE).

2. "Chemical Data Safety Sheet SD-36" (latest revision) (Washington, DC: Manufacturing Chemists' Association).

3. N. Irving Sax, *Dangerous Properties of Industrial Materials* (New York, NY: Reinhold Book Corp., 1984).

⁽²⁾ Manufacturing Chemists' Association, 1825 Connecticut Ave. NW, Washington, DC 20009.

Standard Recommended Practice

External Cathodic Protection of On-Grade Carbon Steel Storage Tank Bottoms

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Revised 2001-06-15
Approved October 1993
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ISBN 1-57590-014-9
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Foreword

It is extremely important to maintain the integrity of on-grade carbon steel storage tanks for both economic and environmental reasons. The proper design, installation, and maintenance of cathodic protection (CP) systems can help maintain the integrity and increase the useful service life of on-grade carbon steel storage tanks.

The purpose of this standard recommended practice is to outline practices and procedures for providing cathodic protection to the soil side of bottoms of on-grade carbon steel storage tanks that are in contact with an electrolyte. Recommendations for both galvanic anode systems and impressed current systems are included. Design criteria for the upgrade of existing tanks as well as for newly constructed tanks are included. This standard is intended for use by personnel planning to install new on-grade carbon steel storage tanks, upgrade cathodic protection on existing storage tanks, or install new cathodic protection on existing storage tanks.

This NACE standard was originally prepared by Task Group T-10A-20, a component of NACE Unit Committee T-10A on Cathodic Protection, in 1993. It was technically revised by Task Group 013 in 2001. Task Group 013 is administered by Specific Technology Group (STG) 35 on Pipelines, Tanks, and Well Casings and sponsored by STGs 03 on Protective Coatings and Linings—Immersion/Buried and STG 05 on Cathodic/Anodic Protection. This standard is issued by NACE International under the auspices of STG 35 on Pipelines, Tanks, and Well Casings.

In NACE standards, the terms *shall*, *must*, *should*, and *may* are used in accordance with the definitions of these terms in the *NACE Publications Style Manual*, 4th ed., Paragraph 7.4.1.9. *Shall* and *must* are used to state mandatory requirements. The term *should* is used to state something good and is recommended but is not mandatory. The term *may* is used to state something considered optional.

NACE International Standard Recommended Practice

External Cathodic Protection of On-Grade Carbon Steel Storage Tank Bottoms

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Section 1: General

1.1 This standard presents guidelines for the design, installation, and maintenance of cathodic protection for the exterior bottoms of on-grade carbon steel storage tanks. Cathodic protection can be installed to protect new or existing tanks, but cannot protect carbon steel surfaces that are not in contact with an electrolyte.

1.2 This standard is applicable to welded, bolted, and riveted carbon steel tanks that are either field- or shop-fabricated.

1.3 It is understood in this standard that cathodic protection may be used alone or in conjunction with protective coatings.

1.4 All cathodic protection systems should be installed with the intent of conducting uninterrupted, safe operations. When cathodic protection is applied, it should be operated continuously to maintain polarization.

1.5 The criteria for cathodic protection are based on current industry standards.

1.6 Corrosion control must be a consideration during the design of on-grade carbon steel storage tanks.

Section 2: Definitions

Amphoteric Metal: A metal that is susceptible to corrosion in both acid and alkaline environments.

Anode: The electrode of an electrochemical cell at which oxidation occurs. Electrons flow away from the anode in the external circuit. Corrosion usually occurs and metal ions enter the solution at the anode.

Backfill: Material placed in a hole to fill the space around the anodes, vent pipe, and buried components of a cathodic protection system.

Cathode: The electrode of an electrochemical cell at which reduction is the principal reaction. Electrons flow toward the cathode in the external circuit.

Cathodic Protection (CP): A technique to reduce the corrosion of a metal surface by making that surface the cathode of an electrochemical cell.

Cell: See *Electrochemical Cell*.

Current Density: The current to or from a unit area of an electrode surface.

Deep Groundbed: One or more anodes installed vertically at a nominal depth of 15 m (50 ft) or more below the earth's surface in a drilled hole for the purpose of supplying cathodic protection.

Differential Aeration Cell: An electrochemical cell, the electromotive force of which is due to a difference in air (oxygen) concentration at one electrode as compared with that at another electrode of the same material.

Electrical Isolation: The condition of being electrically separated from other metallic structures or the environment.

Electrochemical Cell: A system consisting of an anode and a cathode immersed in an electrolyte so as to create an electrical circuit. The anode and cathode may be different metals or dissimilar areas on the same metal surface.

Electrolyte: A chemical substance containing ions that migrate in an electric field.

External Circuit: The wires, connectors, measuring devices, current sources, etc., that are used to bring about or measure the desired electrical conditions within an electrochemical cell. It is this portion of the cell through which electrons travel.

Foreign Structure: Any metallic structure that is not intended as a part of a system under cathodic protection.

Galvanic Anode: A metal that provides sacrificial protection to another metal that is more noble when electrically coupled in an electrolyte. This type of anode is the electron source in one type of cathodic protection.

Groundbed: One or more anodes installed below the earth's surface for the purpose of supplying cathodic protection. For the purposes of this standard, a groundbed is defined as a single anode or group of anodes installed in the electrolyte for the purposes of discharging direct current to the protected structure.

Impressed Current: An electric current supplied by a device employing a power source that is external to the electrode system. (An example is direct current for cathodic protection).

On-Grade Storage Tank: A tank constructed on sand or earthen pads, concrete ringwalls, or concrete pads.

Oxidation: (1) Loss of electrons by a constituent of a chemical reaction. (2) Corrosion of a metal that is exposed to an oxidizing gas at elevated temperatures.

Piping: For the purposes of this standard, this term refers to all piping associated with the transfer of products in and out of storage tanks.

Reduction: Gain of electrons by a constituent of a chemical reaction.

Reference Electrode: An electrode whose open-circuit potential is constant under similar conditions of measurement, which is used for measuring the relative potentials of other electrodes.

Stray-Current Corrosion: Corrosion resulting from current through paths other than the intended circuit, e.g., by any extraneous current in the earth.

Section 3: Preliminary Evaluation and Determination of the Need for Cathodic Protection

3.1 This section outlines the information that should be considered prior to designing a cathodic protection system to protect on-grade carbon steel storage tank bottoms in contact with an electrolyte.

3.2 Site Assessment Information

3.2.1 Prior to designing a cathodic protection system, the following information should be obtained:

- (a) Tank, piping, and grounding construction drawings, including dimensions, etc.
- (b) Site plan and layout
- (c) Date of construction
- (d) Material specifications and manufacturer
- (e) Joint construction (i.e., welded, riveted, etc.)
- (f) Coating specifications
- (g) Existing or proposed cathodic protection systems in the area
- (h) Location of electric power sources
- (i) Electrochemical properties of the tank bedding or padding material
- (j) History of the tank foundation (i.e., whether the tank has been jacked up/leveled, etc.)
- (k) Unusual environmental conditions
- (l) Operating history of the tank, including leak information (internal and external)
- (m) Maintenance history of the tank
- (n) Containment membranes/impervious linings
- (o) Secondary bottoms
- (p) Water table and site drainage information
- (q) Liquid levels maintained in the tank
- (r) Nearby foreign structures
- (s) Type of liquid stored
- (t) Operating temperature
- (u) Electrical grounding

3.3 Predesign Site Appraisal

3.3.1 Determining the Extent of Corrosion on Existing Systems

3.3.1.1 Information regarding the degree of tank-bottom corrosion is useful because considerable bottom damage may require extensive repairs or replacement prior to the installation of cathodic protection.

3.3.1.2 Field procedures for determining the extent of existing corrosion may include:

- (a) Visual inspection
- (b) Tank bottom plate-thickness measurements (ultrasonic testing, coupon analysis, etc.)
- (c) Estimation of general corrosion rates through the use of electrochemical procedures
- (d) Determination of the magnitude and direction of galvanic or stray current transferred to or from the tank through piping and other interconnections
- (e) Determination of soil characteristics including resistivity, pH, chloride ion concentration, sulfide ion concentration, and moisture content
- (f) Estimation of the degree of corrosion deterioration based on comparison with data from similar facilities subjected to similar conditions

3.3.1.3 Foundation characteristics are also important factors in the assessment of the extent of existing corrosion. The pad material of construction, thickness of ringwalls, and water drainage should all be considered.

3.3.1.4 Data pertaining to existing corrosion conditions should be obtained in sufficient quantity to permit reasonable engineering judgments. Statistical procedures should be used in the analysis, if appropriate.

3.3.2 Electrical Isolation

3.3.2.1 Electrical isolation facilities must be compatible with electrical grounding requirements conforming to applicable codes and safety requirements. If the tank bottom is to be cathodically protected, the use of alternative electrical grounding materials, such as galvanized steel and galvanic anodes, should be considered.

3.3.2.2 The designer of a cathodic protection system should consider the possible need for electrical isolation of the tank from piping and other interconnecting structures. Isolation may be necessary for effective cathodic protection or safety considerations.

3.3.2.3 Electrical isolation of interconnecting piping can be accomplished through the use of isolating flanges, dielectric bushings or unions, or other devices specifically designed for this purpose. These devices shall be rated for the proper operating pressure and be compatible with the products being transported.

3.3.2.4 Polarization cells, lightning arresters, grounding cells, and other decoupling devices may be useful in some situations for maintaining isolation under normal operating conditions and providing protection for an isolating device during lightning strikes, power surges, and other abnormal situations.

3.3.2.5 Tests to determine tank electrical characteristics include:

- (a) Tank-to-earth resistance tests
- (b) Tank-to-grounding system resistance and potential tests
- (c) Tank-to-electrolyte potential tests
- (d) Electrical continuity tests for mechanical joints in interconnecting piping systems
- (e) Electrical leakage tests for isolating fittings installed in interconnecting piping and between the tanks and safety ground conductors

3.3.3 Cathodic Protection Type, Current Requirements, and Anode Configuration

3.3.3.1 Soil resistivity tests should be performed in sufficient quantity as to aid in determining the type of cathodic protection (galvanic or impressed current) required and the configuration for the anode system. Figure 1 illustrates the four-pin method of soil resistivity testing.

3.3.3.2 Resistivities can be determined using the four-pin method described in ASTM⁽¹⁾ G 57,¹ with pin spacings corresponding to depths of at least that expected for the anode system, or by using an equivalent testing method (in very dry environments, electromagnetic conductivity testing may be used to measure resistivities).² The resistivity measurements should be obtained in sufficient detail to identify possible variations with respect to depth and location. As a general guideline, resistivity data should be obtained at a minimum of two locations per tank.

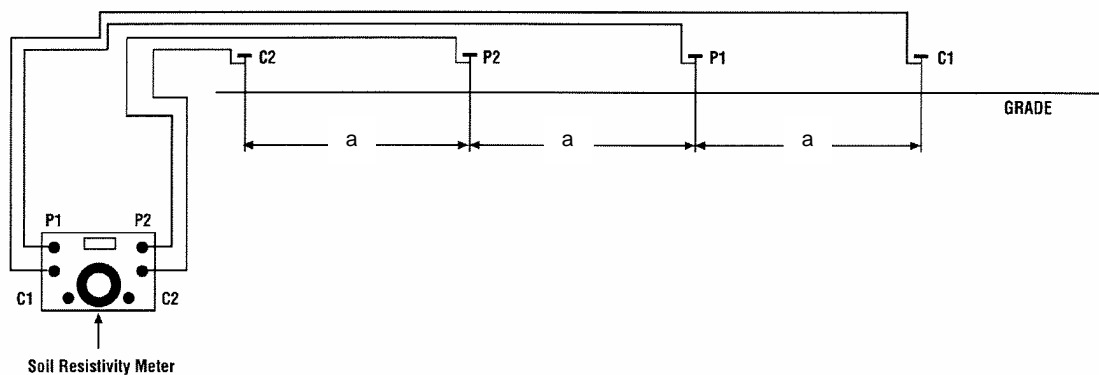


Figure 1: Soil Resistivity Testing (Four-Pin Method)
Note: a = Depth of interest for the soil resistivity measurement.

⁽¹⁾ American Society for Testing and Materials (ASTM), 100 Barr Harbor Dr., West Conshohocken, P.A. 19428.

3.3.3.3 If deep groundbeds are considered, resistivities should be analyzed using procedures described by Barnes³ to determine conditions on a layer-by-layer basis. On-site resistivity data can be supplemented with geological data including subsurface stratigraphy, hydrology, and lithology. Sources for geological information include water well drillers, oil and gas production companies, the U.S. Geological Survey Office,⁽²⁾ and other regulatory agencies.

3.3.3.4 Cathodic protection current requirements can be estimated using test anode arrays simulating the type of groundbed planned. Test currents can be applied using suitable sources of direct current. Test groundbeds can include driven rods, anode systems for adjacent cathodic protection installations, or other temporary structures that are electrically separated from the tank being tested. Small-diameter anode test wells may be appropriate and should be considered if extensive use of deep anode groundbeds is being considered. Figure 2 illustrates a temporary groundbed for current requirement testing.

3.3.4 Stray Currents

3.3.4.1 The presence of stray earth currents may result in cathodic protection current requirements that are greater than those required under natural conditions. Possible sources of stray current include DC-operated rail systems and mining operations, other cathodic protection systems, welding equipment, and high-voltage direct current (HVDC) transmission systems.

3.3.4.1.1 Field tests to determine whether stray currents are a concern include those that provide tank-to-electrolyte and structure-to-electrolyte potential measurements on adjacent structures, earth gradient measurements, and current flow measurements on tank piping and safety grounding conductors.

3.3.4.1.2 Possible interference effects caused by adjacent cathodic protection systems should be determined by interrupting the current output using a known timing cycle. Structure-to-electrolyte potentials and other parameters should be monitored over a minimum 24-hour period in areas where dynamic stray currents or transient effects are expected to be a concern. Recording instruments can be used for this purpose. Figure 3 illustrates stray current corrosion.

3.3.4.1.3 Cathodic protection designs should incorporate every practical effort to minimize electrical interference on structures not included in the protection system. Predesign test results can be analyzed to determine the possible need for stray-current control provisions in the cathodic protection system.

⁽²⁾ U.S. Geological Survey Office, P.O. Box 25046, Federal Center, Denver, CO 80225.

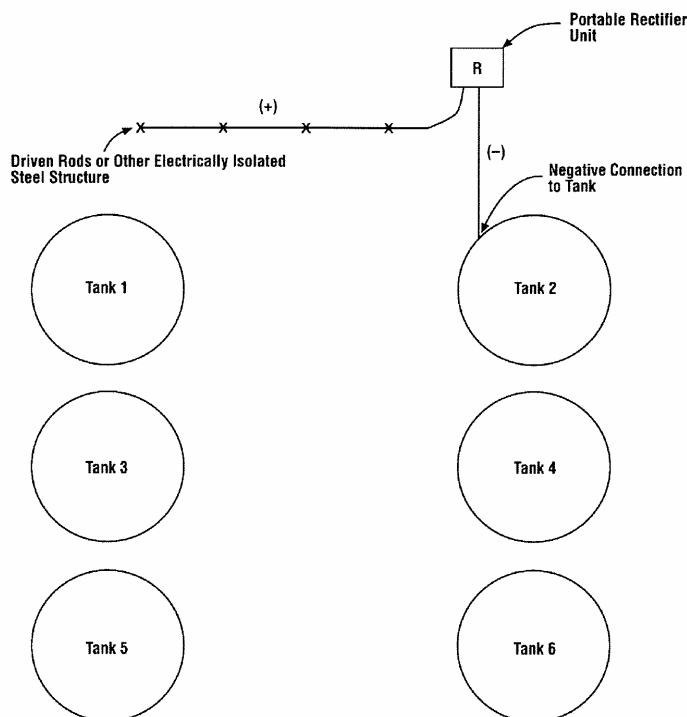


Figure 2: Temporary Groundbed for Current Requirement Testing

Section 4: Criteria for Cathodic Protection

4.1 This section lists criteria for cathodic protection that, if complied with either separately or collectively, indicate that cathodic protection of an on-grade carbon steel storage tank bottom has been achieved.

4.2 General

4.2.1 The objective of using cathodic protection is to control the corrosion of an on-grade carbon steel storage tank bottom in contact with an electrolyte. The selection of a particular criterion for achieving this objective depends, in part, on prior experience with

similar tank bottoms and environments in which the criterion has been successfully used.

4.2.2 The criteria in Paragraph 4.3 were developed through laboratory experiments or were determined empirically by evaluating data obtained from successfully operated cathodic protection systems. It is not intended that personnel responsible for corrosion control be limited to operating under these criteria if it can be demonstrated by other means that the control of corrosion has been achieved.

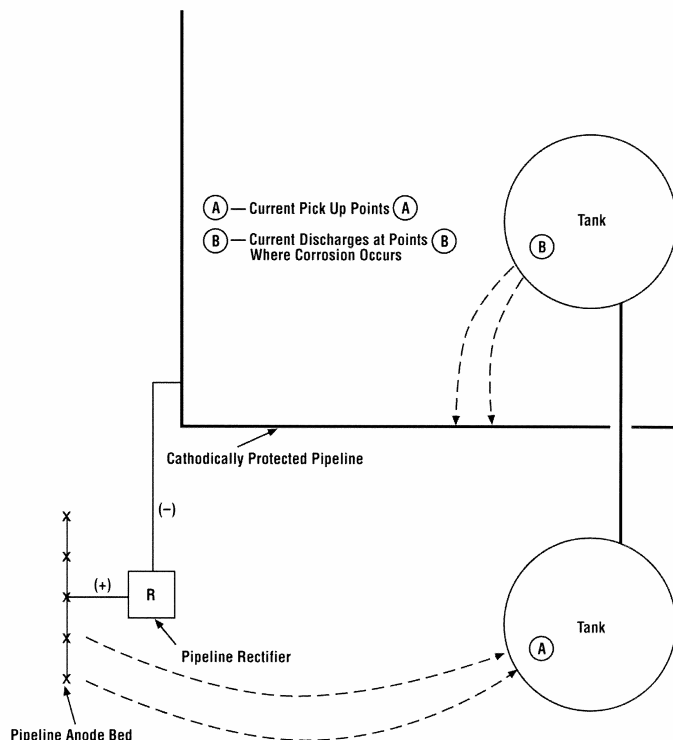


Figure 3: Stray Current Corrosion

4.2.3 Potential measurements on storage tanks shall be made with the reference electrode located as close as possible to the tank bottom. On most tanks, measurements should be taken at the perimeter, near the center of the tank bottom, and at various points in between. Consideration must be given to voltage drops other than those across the structure-to-electrolyte boundary, the presence of dissimilar metals, and the influence of other structures. These factors may interfere with valid interpretation of potential measurements. Also, measurements made with a reference electrode located on asphalt pavement or a concrete slab or outside the concrete wall may be in error.

4.3 Criteria for Corrosion Control of Carbon Steel Tank Bottoms

4.3.1 Corrosion control can be achieved at various levels of cathodic polarization depending on environmental conditions. However, in the absence of specific data that demonstrate that cathodic protection has been achieved, one or more of the following must apply to the system:

4.3.1.1 A negative (cathodic) potential of at least 850 mV with the cathodic protection current applied. This potential shall be measured with

respect to a saturated copper/copper sulfate reference electrode (CSE) contacting the electrolyte. Consideration must be given to voltage drops other than those across the structure-to-electrolyte boundary for valid interpretation of this voltage measurement.

4.3.1.1.1 Consideration is understood to mean the application of sound engineering practice in determining the significance of voltage drops by methods such as:

- (a) Measuring or calculating the voltage drop(s),
- (b) Reviewing the historical performance of the cathodic protection system,
- (c) Evaluating the physical and electrical characteristics of the tank bottom and its environment, and
- (d) Determining whether or not there is physical evidence of corrosion.

4.3.1.2 A negative polarized potential of at least 850 mV relative to a CSE.

4.3.1.3 A minimum of 100 mV of cathodic polarization between the carbon steel surface of the tank bottom and a stable reference electrode

contacting the electrolyte. The formation or decay of polarization may be measured to satisfy this criterion.

4.4 Reference Electrodes

4.4.1 Other standard reference electrodes may be substituted for the CSE. Two commonly used reference electrodes are listed below. The voltages given are equivalent (at 25°C [77°F]) to a negative 850 mV potential referred to a CSE:

- (a) Saturated silver/silver chloride reference electrode: a negative 780 mV potential
- (b) High-purity zinc (99.99%): a positive 250-mV potential (see Paragraph 7.3.4)

4.4.2 Stationary (permanently installed) reference electrodes may assist in measuring potentials under the tank. Stationary electrodes may be encapsulated in an appropriate backfill material.

4.5 Special Considerations

4.5.1 Special cases, such as stray currents and stray electrical gradients, that require the use of criteria different from those listed above may exist.

4.5.2 Coupons and electrical resistance probes may be useful in evaluating the effectiveness of the cathodic protection system.

4.5.3 Conditions in which cathodic protection is ineffective or only partially effective sometimes exist. Such conditions may include the following:

- (a) Elevated temperatures
- (b) Disbonded coatings
- (c) Shielding
- (d) Bacterial attack
- (e) Unusual contaminants in the electrolyte
- (f) Areas of the tank bottom that do not come into contact with the electrolyte
- (g) Dry tank cushion

4.5.4 Rocks, clay deposits, or clumps under tank bottom plates can promote the formation of localized corrosion activity, which is difficult to monitor or evaluate.

Section 5: General Considerations for Cathodic Protection Design

5.1 This section recommends procedures and considerations that apply to the design of cathodic protection systems for on-grade, single- and double-bottom carbon steel storage tanks.

5.2 Cathodic Protection Objectives and System Characteristics

5.2.1 The major objectives for the design of a cathodic protection system are:

- (a) To protect the tank bottom from soil-side corrosion
- (b) To provide sufficient and uniformly distributed current
- (c) To provide a design life commensurate with the design life of the tank bottom or to provide for periodic anode replacement
- (d) To minimize interference currents
- (e) To provide adequate allowance for anticipated changes in current requirements for protection
- (f) To locate and install system components where the possibility of damage is minimal
- (g) To provide adequate monitoring facilities to permit a determination of the system's performance (see Paragraph 11.2)

5.2.2 General characteristics of impressed current and galvanic current cathodic protection systems are listed

in Table 1. Impressed current systems are usually used if the service temperature is elevated, or if other factors require higher current densities. Impressed current systems are also used if higher driving potentials are needed due to the presence of high-resistance electrolytes, or if the economic benefit of such a system is considered significant to the project.

5.2.3 An impressed current cathodic protection system is powered by an external source of direct current. The positive terminal of the direct current source is connected through insulated conductors to the anode system. The negative terminal of the direct current source is electrically connected to the tank bottom to be protected. Anode systems for on-grade storage tanks can include shallow groundbeds around or under the tank and/or deep anode groundbeds.

5.2.3.1 Satisfactory anode materials include mixed-metal oxides, polymer carbon, graphite, high-silicon chromium-bearing cast iron, platinized niobium (columbium), platinized titanium, scrap metal, and belowgrade metallic structures that have been removed from service and cleaned of contaminants. Anode selection should be based on soil chemistry, contaminants, and the compatibility of the anode with the environment.

5.2.4 Galvanic current cathodic protection systems operate on the principle of dissimilar-metals corrosion. The anode in a galvanic current system must be more electrochemically active than the structure to be protected. Cathodic protection using a galvanic system

is afforded by providing an electrical connection between the anode system and the storage tank bottom. Typical galvanic current anode materials for storage tank bottom applications include magnesium and zinc.

TABLE 1
Cathodic Protection System Characteristics

Galvanic Current	Impressed Current
No external power required	External power required
Fixed, limited driving voltage	Driving voltage can be varied
Limited current	Current can be varied
Satisfies small current requirements	Satisfies high current requirements
Used in lower-resistivity environments	Used in higher-resistivity environments
Usually no stray current interference	Must consider interference with other structures

5.3 In the design of a cathodic protection system, the following shall be considered:

- (a) Recognition of hazardous conditions prevailing at the site and the selection and specification of materials and installation practices that ensure safe installation and operation
- (b) Compliance with all applicable governmental codes and owner requirements
- (c) Selection and specification of materials and installation practices that ensure dependable and economic operation of the system throughout its intended operating life
- (d) Design of proposed installation to minimize stray currents
- (e) Avoiding excessive levels of cathodic protection, which may cause coating disbondment and possible damage to high-strength and special alloy steels
- (f) If amphoteric metals are involved (i.e., lead, tin, aluminum), avoiding high or low pH conditions that could cause corrosion
- (g) Presence of secondary containment systems

5.4 Current Requirement

5.4.1 The preferred method of determining the current requirements for achieving a given level of protection on an existing tank bottom is to test the tank bottom using a temporary cathodic protection system. Alternately, a current density can be used for design purposes based on a current density successfully used at the same facility or at a facility with similar characteristics.

5.4.2 For design purposes, current requirements on new or proposed tank bottoms may be established by calculating surface areas and applying a protective current density based on the size of the tank, the electrochemical characteristics of the environment, the service temperature, and the parameters of the groundbed. Design current densities of 10 to 20 mA/m² (1 to 2 mA/ft²) of bare tank bottom surface are generally sufficient. Systems exposed to chemistry involving chlorides, sulfides, or bacteria or to elevated

service temperatures require more current. The history of other tanks in the same environment should be considered when choosing a design current density.

5.4.3 Care must be exercised to ensure that anode type and placement result in uniform distribution of protective current to the tank bottom surfaces.

5.4.4 Liquid levels within tanks must be sufficient to ensure that the entire tank bottom is in intimate contact with an electrolyte while establishing current requirements and testing applied protection levels. Adequate liquid levels are important to maintaining polarization.

5.4.4.1 As the liquid level increases (and more of the tank bottom contacts the electrolyte), the protective current requirement increases and the potential measured may decrease due to the increased surface area of steel contacting the electrolyte.

5.5 Tank System Configuration

5.5.1 Design, materials, and construction procedures that do not create shielding conditions should be used.

5.5.2 Nonwelded mechanical joints might not be electrically continuous. Electrical continuity can be ensured by bonding existing joints.

5.5.3 If electrical isolation is required, care must be taken to assure that the isolation is not shorted, bypassed, etc.

5.6 Special consideration should be given to the presence of sulfides, chlorides, bacteria, coatings, elevated temperatures, shielding, pH conditions, treated tank padding material, soil/groundwater contamination, dissimilar metals, and pad/concrete/metal interface at the ringwall, as well as any heating or refrigeration coils under tank bottoms. Clean, fine sand is the preferred tank pad material.

5.7 On-grade tanks that are set on solid concrete or asphalt pad foundations generally require specialized measures for corrosion protection, because cathodic protection may be ineffective. In this circumstance, the external surface of the tank bottom should be coated. In all cases, steps should be taken to ensure that water does not migrate between the tank bottom and the pad.

5.7.1 Providing electrical isolation between the reinforcing steel and the tank bottom should be considered if a concrete ringwall or pad is used.

5.8 Design Drawings and Specifications

5.8.1 Specifications should be prepared for all materials and installation procedures that are used during construction of the cathodic protection system.

5.8.2 Suitable drawings should be prepared to show the overall layout of the tank bottoms to be protected and the cathodic protection system and associated appurtenances.

Section 6: Design Considerations for Impressed Current Cathodic Protection

6.1 This section recommends procedures and considerations that specifically apply to the design of impressed current cathodic protection systems for on-grade carbon steel storage tank bottoms.

6.2 Impressed Current Anode Systems

6.2.1 Impressed current anodes shall be connected with an insulated cable, either singularly or in groups, to the positive terminal of a direct current source such as a rectifier or DC generator. The tank bottom shall be electrically connected to the negative terminal. Cable insulation should be selected based on the anticipated environmental conditions and should be resistant to oil and water.

6.2.2 Anode groundbed configurations may be vertical, angled, deep, or horizontal, as illustrated in Figures 4 through 7. Anodes may be installed in a distributed fashion under tank bottoms. The selection of anode configuration is dependent on environmental factors, current requirements, the size and type of tank bottom to be protected, whether the tank is of new or existing construction, and whether it is a single- or double-bottom tank.

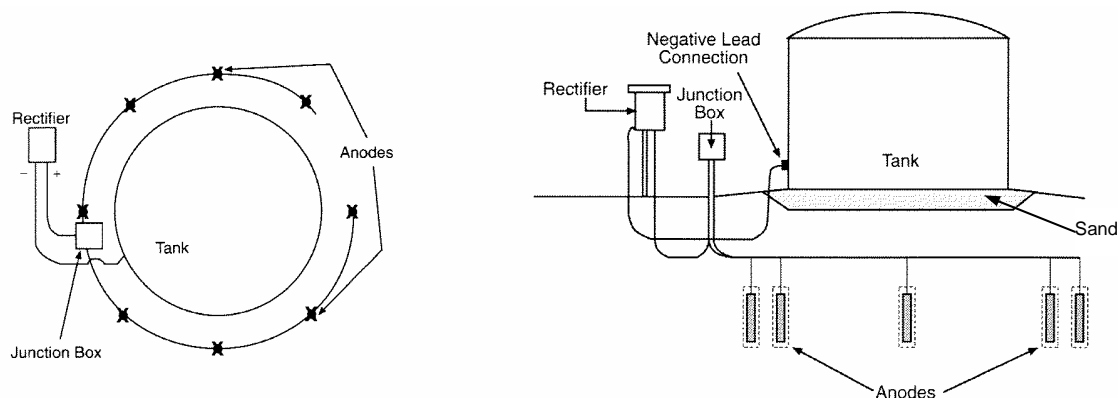


Figure 4: Vertically Drilled Anode CP System

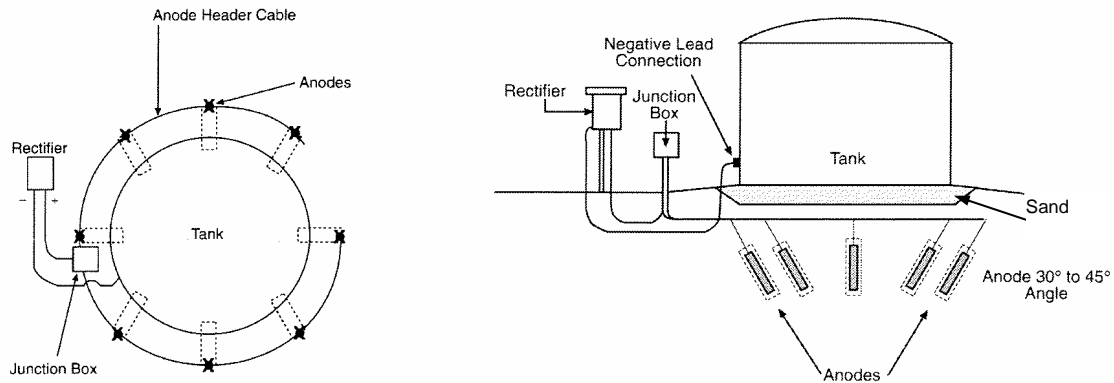


Figure 5: Angled Anode Cathodic Protection System

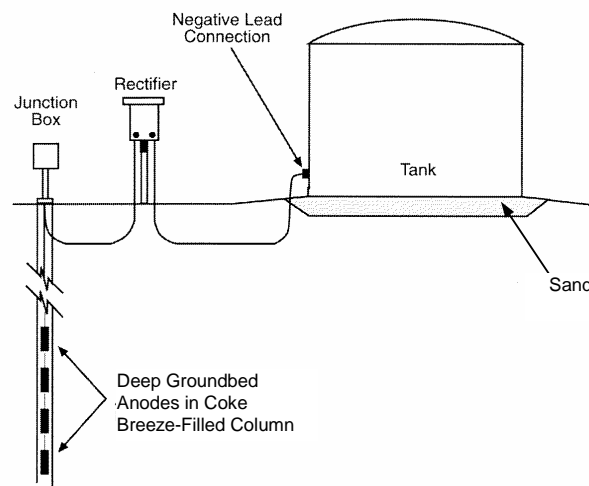


Figure 6: Deep Anode Groundbed

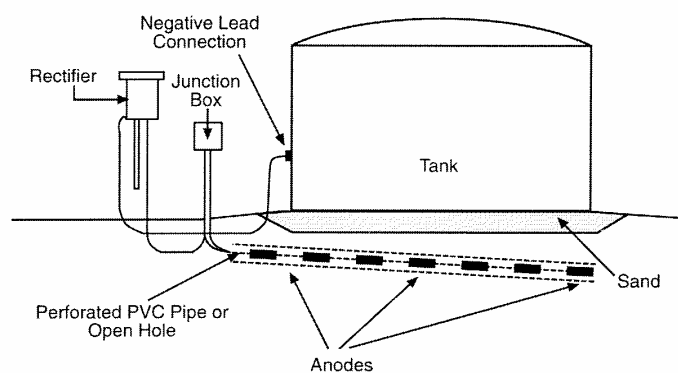


Figure 7: Horizontally Installed Anode Groundbed

6.2.3 Deep anode systems should be designed and installed in accordance with NACE Standard RP0572.⁴

6.2.4 Anode materials have varying rates of deterioration when discharging current. Therefore, for

a given output, the anode life depends on the environment, anode material, anode weight, and the number of anodes in the cathodic protection system. Established anode performance data should be used to calculate the probable life of the system.

NOTE: Platinized niobium (columbium) and polymeric anodes should not be used in hydrocarbon-contaminated environments.

6.2.5 The useful life of impressed current anodes can be lengthened by the use of special backfill around the anodes. The most commonly used backfill materials are metallurgical coal coke and calcined petroleum coke. Because coke is noble compared to carbon steel, coke should not be allowed to come into contact with the tank bottom.

6.2.6 In the design of an extensive, distributed-anode impressed current system, the voltage and current attenuation along the anode and the anode-connecting (header) cable should be considered. In such cases, the design objective should be to optimize anode system length, anode size and spacing, and cable size in order to achieve effective corrosion control over the entire surface of each tank bottom.

6.2.7 Suitable provisions for venting the anodes should be made in situations in which it is anticipated that entrapment of gas generated by anodic reactions could impair the ability of the impressed current grounded to deliver the required current. Venting systems must be designed to prevent contaminants from getting into the venting system.

6.3 Safety

6.3.1 All impressed current systems must be designed with safety in mind. Care must be taken to ensure that all cables are protected from physical damage and the possibility of arcing.

6.3.2 Rectifiers and junction boxes must meet regulatory requirements for the specific location and environment in which they are installed. Such locations shall be determined by reviewing regulatory agency and prevailing industrial codes.

6.3.2.1 Consideration should be given to locating isolating devices, junction boxes, and rectifiers outside hazardous areas in case sparks or arcs occur during testing.

6.3.3 In order to prevent arcing, care must be exercised when working on piping attached to tanks with cathodic protection applied. When cathodic protection systems are turned off, sufficient time must be allowed for depolarization before opening connections. Bonding cables must be used when parting piping joints.

Section 7: Design Considerations for Galvanic Anode Cathodic Protection

7.1 This section describes the factors that should be considered in the design of external corrosion protection of on-grade carbon steel storage tank bottoms without secondary containment that are protected by galvanic anode cathodic protection.

7.2 Galvanic protection systems may be applied to a tank bottom if the carbon steel surface area exposed to the electrolyte can be minimized through the application of a dielectric coating, the surface area is small due to the tank size or configuration, or no power source or impressed current source is available.

7.2.1 Galvanic anodes should be connected to the tank bottom through a test station so that anode performance and voltage drops can be monitored.

7.2.2 In applications for which the tank bottom is either uncoated or large due to the tank size or configuration, the use of impressed current cathodic protection should be considered to minimize the cost of the protection system. Section 6 provides more information regarding the design considerations for impressed current cathodic protection systems.

7.3 Galvanic Anode Selection

7.3.1 The three most common types of galvanic anodes effective in soil environments are standard magnesium, high-potential magnesium, and high-purity zinc.

7.3.2 The selection and use of these anodes should be based on the current requirements of the tank bottom, the soil conditions, the temperature of the tank bottom, and the cost of the materials.

7.3.3 The current available from each type of anode depends greatly on the soil conditions, the anode shape (whether bar, block, or ribbon), and the driving potential of the anode.

7.3.4 If high-purity zinc anodes are employed, care should be exercised to ensure that the anodes meet the requirements of ASTM B 4185 Type II anode material. The purity of the zinc can greatly affect the performance of the material as a galvanic anode for soil applications.

7.3.5 Zinc anodes should not be used if the temperature of the anode environment is above 49°C (120°F). Higher temperatures can cause passivation of the anode. The presence of salts such as carbonates,

bicarbonates, or nitrates in the electrolyte may also affect the performance of zinc as an anode material.

7.3.6 Galvanic anode performance may be enhanced in most soils by using special backfill material. Mixtures of gypsum, bentonite, and sodium sulfate are the most common.

7.3.7 Galvanic anodes (except for rebar-type anodes) should be supplied with adequate lead wire attached by the anode supplier.

7.3.7.1 Lead wire should be at least 2 mm in diameter (#12 AWG [American Wire Gauge.]) Cable insulation should be selected based on the anticipated environmental conditions and should typically be resistant to oil and water.

Section 8: Design Considerations — Cathodic Protection for Tanks with Replacement Bottoms or Release-Prevention Barriers

8.1 Introduction

8.1.1 Release-prevention barriers and replacement tank bottoms can be used together or separately.

8.1.2 Release-prevention barriers and/or secondary carbon steel tank bottoms may shield the carbon steel surface of the primary tank bottom from the flow of cathodic protection current, resulting in a lack of adequate cathodic protection.

8.1.3 Any impact (i.e., corrosiveness) that the fill material beneath or between the tank bottoms could have on the cathodic protection system should be considered.

8.2 Release-Prevention Barriers

8.2.1 Impervious membranes or liners constructed of a nonconductive material used as a release-prevention barrier can prevent the flow of cathodic protection current from anodes located outside the barrier envelope. Anodes must be placed between the barrier and the carbon steel tank bottom so that current flows to the surfaces requiring protection.

If release-prevention barriers made of conductive material are used with a cathodic protection system with anodes outside the space contained by the barrier, the barrier must maintain a resistance low enough for sufficient cathodic protection current to flow to the tank bottom.

8.2.2 Stationary reference electrodes and/or portable reference electrode insertion tubes must be located between the carbon steel tank bottom and the barrier or between the bottoms to obtain accurate structure-to-electrolyte data.

8.3 Replacement Tank Bottoms

8.3.1 If a replacement tank bottom is installed in an existing tank over an original bottom so that there is an electrolyte between the two tank bottoms, galvanic corrosion activity can develop on the new bottom, resulting in premature failure.

8.3.2 Cathodic protection should be considered for the primary (new) bottom. The anodes and reference electrodes or nonconductive reference electrode insertion tubes must be placed in the electrolyte between the two bottoms. Figure 8 illustrates a typical double-bottom cathodic protection layout.

8.3.3 The installation of a nonconductive, impervious membrane or liner above the original bottom reduces galvanic corrosion activity on the replacement bottom, reducing the current required for cathodic protection.

8.3.4 If the original tank bottom is removed and replaced with a new bottom, the cathodic protection design should be that utilized for a standard, single-bottom tank.

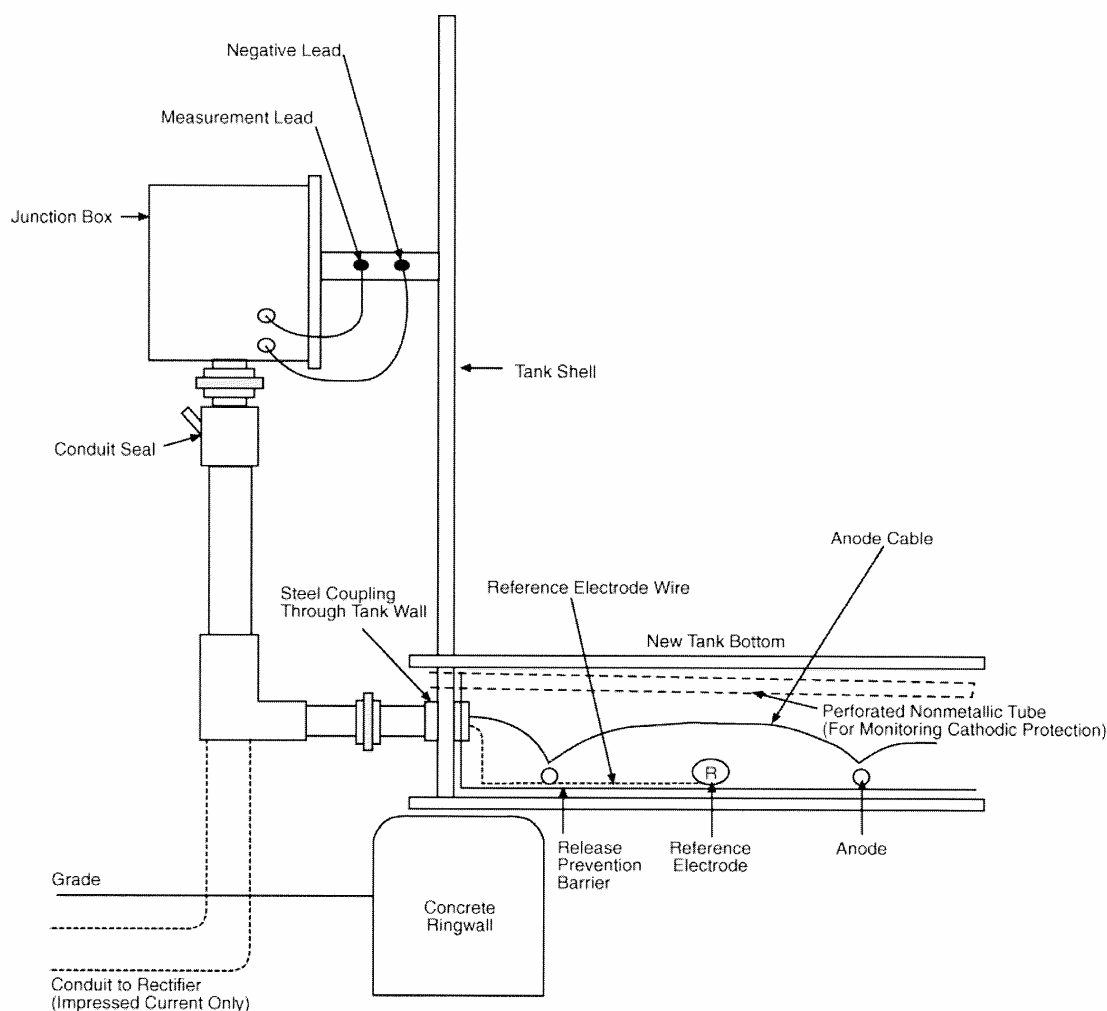


Figure 8: Typical Double-Bottom Cathodic Protection Layout (Impressed or Sacrificial)

8.4 Cathodic Protection Anodes

8.4.1 Either impressed current or galvanic anode cathodic protection may be used.

8.4.1.1 Galvanic anodes may be magnesium or zinc. Figure 9 illustrates a typical double-bottom galvanic anode design.

8.4.1.2 Anode materials that may be used for impressed current systems include mixed-metal oxides, polymer carbon, graphite, high-silicon chromium-bearing cast iron, platinized niobium (columbium), platinized titanium, scrap metal, and below-grade metallic structures that have been removed from service. Figure 10 illustrates a typical new tank or double-bottom impressed current anode design.

8.4.1.3 Due to the depolarizing effect of oxidation by-products (typically chlorine, oxygen,

or carbon dioxide) migrating from the anode to the steel cathode, the current density for protection with an impressed current system may be higher than that required for a galvanic anode system.

8.4.2 Adequate space must be provided between the two tank bottoms to allow for installation of a cathodic protection system with uniform current distribution from the anodes. Due to limited space between bottoms, close anode spacing may be required to improve current distribution.

Impressed current anodes must not contact the carbon steel surfaces of the tank.

8.4.4 Anodes must be installed in a conductive electrolyte. The electrolyte must be sufficiently compacted as to prevent settlement of the replacement tank bottom.

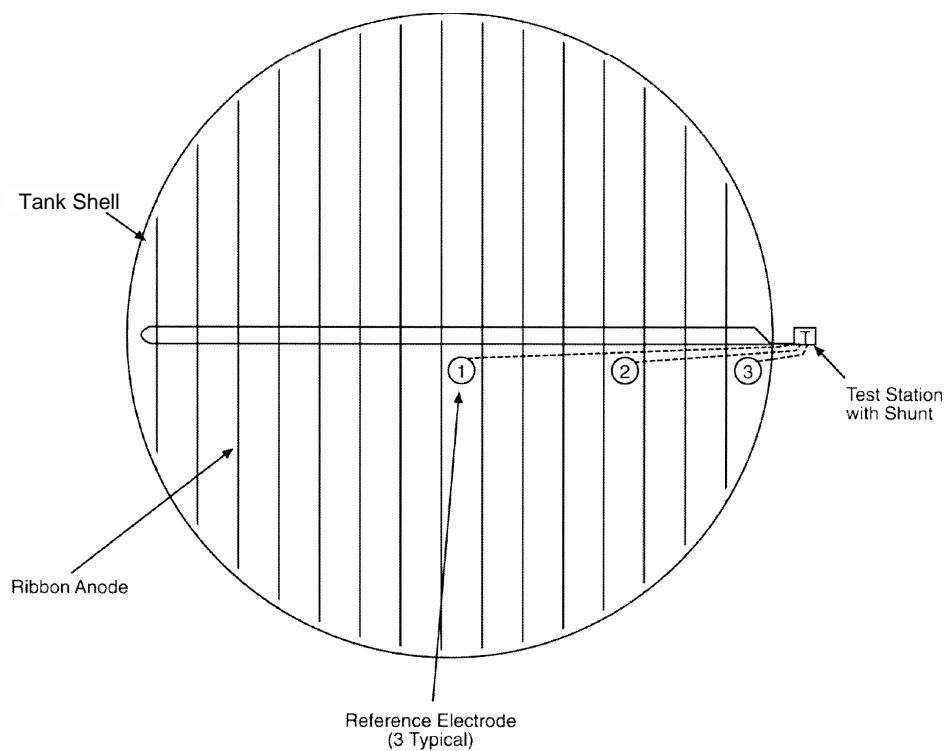


Figure 9: Typical Double-Bottom Galvanic Anode Design

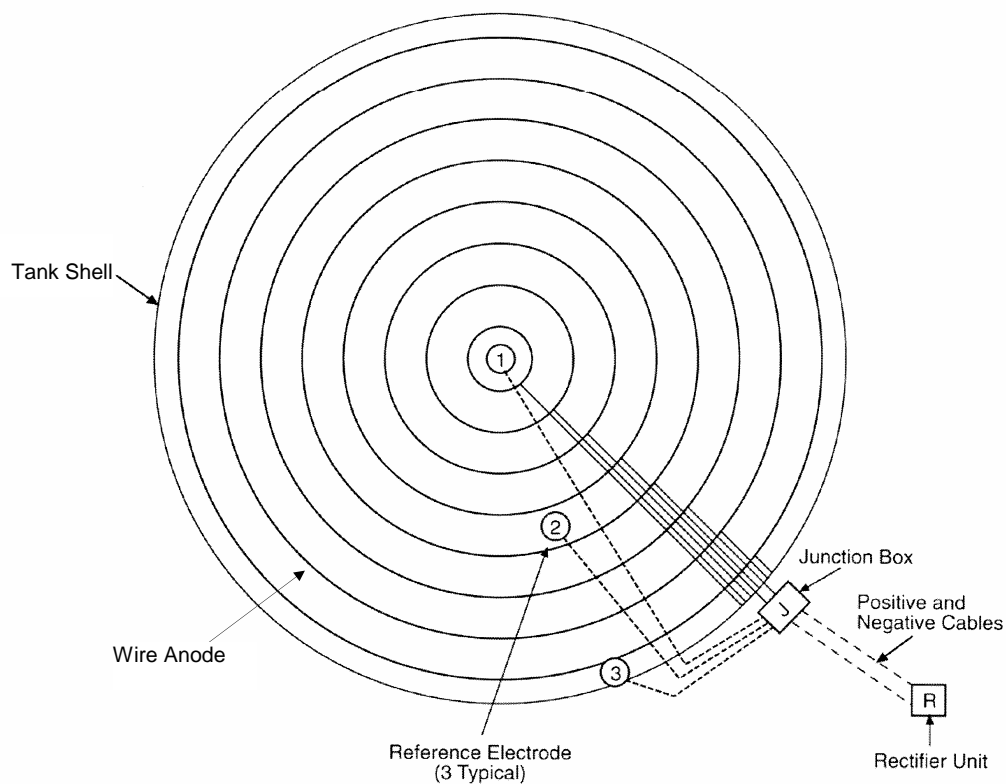


Figure 10: Typical New Tank or Double-Bottom Impressed Current Anode Design

Section 9: Installation Considerations

9.1 This section recommends elements to consider during the installation of cathodic protection systems for on-grade carbon steel storage tank bottoms.

9.2 Preparation

9.2.1 Materials should be inspected prior to installation in order to ensure that specifications have been met.

9.2.2 Installation practices shall conform to all applicable regulatory agencies codes and requirements.

9.3 Anode Installation

9.3.1 Anodes should be installed as designed. Care must be taken to ensure that the anodes do not come into electrical contact with any piping or tankage during installation.

9.3.2 Slack should be allowed in the anode lead wires to avoid possible damage due to settlement of the tank and surrounding soils. Anodes, lead wires, and connections should be handled with care to prevent damage or breakage.

9.3.3 The anode lead wires should be extended to the side of the tank away from the construction to minimize possible damage. After the tank foundation has been prepared and the tank set in place, the wires should be terminated in a test station or junction box, which may include shunts for measuring anode current outputs.

9.4 Reference Electrodes

9.4.1 Stationary reference electrodes or nonconductive, perforated tubes for temporary installation of a portable reference electrode should be installed under all tanks regardless of the groundbed type and location.

9.4.1.1 Stationary reference electrodes may be prepackaged in a backfill and placed in the soil

under the tank bottom or positioned inside the perforated reference electrode access piping. Reference electrodes placed inside access piping should be surrounded with a backfill material designed to provide contact between the electrode and the electrolyte outside the pipe. If practical, provisions should be made for future verification of all stationary reference electrode potentials with portable reference electrodes.

9.4.1.2 Reference electrode access piping must have some means of contact with the electrolyte and should have at least one end accessible from outside the tank shell. This contact can be through the use of holes, slits, or not capping the end of the piping beneath the tank. Perforations and slots should be designed to minimize entry of tank pad material. Portable reference electrodes shall be inserted through the inside diameter of the access pipe with a nonmetallic material such as small-diameter polyvinyl chloride (PVC) pipe. Inserting a reference electrode with metallic tape, bare wires, etc., may adversely affect potential readings. If necessary, water should be injected inside the access pipe to establish continuity between the electrode and the electrolyte. Deionized water should be used for double-bottom tanks or tanks with secondary containment.

9.4.2 For existing tanks, reference electrode access piping should be installed under the tank with horizontal drilling equipment capable of providing guidance and directional control to prevent tank bottom damage and to ensure accurate placement of the piping. Consideration must be given to the structural aspects of the tank padding and foundation to ensure that support capabilities are not adversely affected. Figure 11 illustrates the placement of perforated pipe installed for a reference electrode.

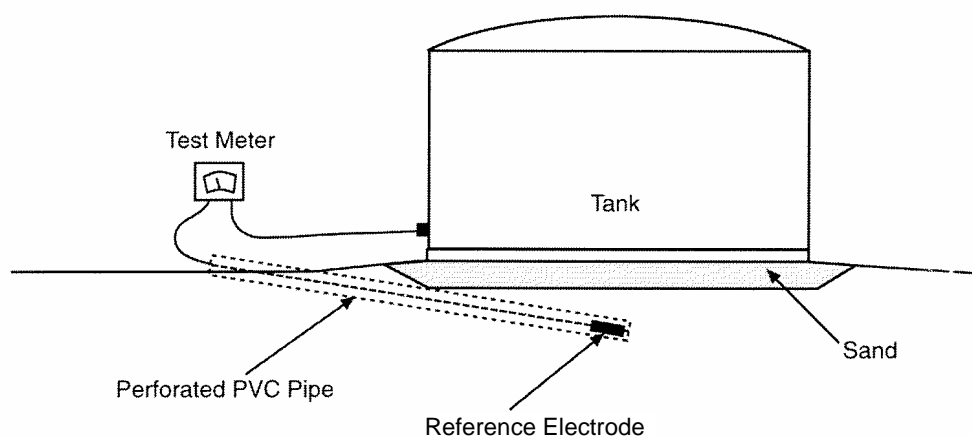


Figure 11: Perforated Pipe Installed for Reference Electrode

NOTE: Special consideration must be given during the design and installation of access pipes to assure that any tank-containment system is not breached.

CAUTION: Extreme caution must be exercised when boring or water jetting under tanks.

9.4.2.1 A constant distance should be maintained from the tank bottom to the reference electrode. Increasing space between tank bottom and reference electrode increases the voltage drop.

9.5 Test Stations and Junction Boxes

9.5.1 Test stations or junction boxes for potential and current measurements should be provided at sufficient locations to facilitate cathodic protection testing.

9.5.2 The test station or junction box should be mounted on or near the side of the tank in an area that is protected from vehicular traffic.

9.5.3 The test station or junction box should allow for disconnection of the anodes to facilitate current measurements and potential measurements for voltage drop as required to evaluate the protection level. If desired, test leads from buried reference electrodes can be terminated in the same test station as tank bottom test wires.

9.5.4 Junction boxes can be used to connect continuity bonds or protective devices.

9.5.5 The test station or junction box in a galvanic system may be equipped with calibrated resistors (shunts) in connections between the anodes and the tank to measure the anode current output and thus the estimated anode life. Shunts are typically rated between 0.001 and 0.1 ohm.

9.5.6 The test station or junction box should be clearly marked and accessible for future monitoring of the tank bottom and, if possible, should be attached to the tank.

9.5.7 All lead wires to the test station or junction box should be protected from damage by a minimum 46-cm (18-in.) burial and/or placement within a conduit. Warning tape may be installed over direct-buried cables to prevent the possibility of damage during future excavation.

9.6 Safety Considerations

9.6.1 All personnel to be involved in the installation of the cathodic protection system should participate in a thorough safety-training program.

9.6.2 All underground facilities, including buried electric cables and pipelines in the affected areas, should be located and marked prior to digging.

9.6.3 All utility companies and other companies with facilities crossing the work areas should be notified and their affected structures located and marked prior to digging.

9.6.4 All areas with low overhead wires, pipelines, and other structures should be located and noted prior to any construction.

9.6.5 Operations and maintenance personnel should be notified of pending construction to coordinate necessary shutdowns or emergency considerations.

Section 10: Energizing and Testing

10.1 This section discusses factors that should be considered when energizing and testing a cathodic protection system for on-grade carbon steel storage tank bottoms. If the tank has a secondary containment system, suitable access ports through the ringwall must be provided for testing.

10.2 Design Parameters

10.2.1 Knowledge of the performance criteria considered during the design of a cathodic protection system as well as the operational limits of cathodic protection devices and hardware should be available to the personnel setting operating levels for the cathodic protection system.

10.3 Initial Data

10.3.1 Verification of cathodic protection devices and hardware, such as the following, should be done prior to energizing:

- (a) Location of anodes
- (b) Ratings of impressed current sources
- (c) Location of reference electrodes
- (d) Location of test facilities
- (e) Location of cathodic protection system cables

10.3.2 Prior to energizing the cathodic protection system, the following data and information should be collected:

- (a) Tank bottom-to-electrolyte potentials
- (b) Pipe-to-electrolyte potentials on connected piping
- (c) Verification of dielectric isolation
- (d) Foreign structure-to-electrolyte potentials
- (e) Test coupon data
- (f) Fluid level in the tank during testing, and
- (f) Corrosion-rate probe data.

10.3.3 All initial baseline data should be documented and the records maintained for the life of the cathodic protection system or the on-grade storage tank. Any deviations from the design or as-built documentation should be noted and included with the initial baseline data.

10.3.4 When measuring the structure-to-electrolyte potential, the portable reference electrodes should be placed at sufficient intervals around the perimeter and under the tank to ensure the potentials measured are representative of the entire tank bottom. The potential measured at the perimeter of a large-diameter tank does not represent the potential at the center of the tank.

10.4 Current Adjustment

10.4.1 The desired operating level of a cathodic protection system must often be determined by a series of trial tests at various operating levels. The specific operating level depends on the criterion for cathodic protection used for the on-grade storage tank(s). Section 4 defines the various criteria for achieving cathodic protection of on-grade carbon steel storage tank bottoms. Time required to achieve polarization on a bare tank bottom can be different from tank to tank.

10.4.2 When the operating levels of cathodic protection systems are adjusted, consideration must be given to the effect of stray current on adjacent structures. Owners of these structures should be notified of the installation of a new cathodic protection system.

10.4.2.1 Among the structures that should be considered as being possibly affected by stray current are:

- (a) On-grade and buried storage tanks
- (b) Piping separated from the tank(s) by high-resistance fittings
- (c) Buried electric facilities
- (d) Buried fire-protection piping
- (e) Buried water piping
- (f) Transmission or distribution piping serving storage tank(s)
- (g) Municipal or public utility structures serving the facility in which a storage tank(s) is located
- (h) Fencing

10.4.2.2 Structures that may contain discontinuous fittings or joints, such as cast iron systems, ductile iron piping systems, or piping with mechanically connected fittings, require special attention to ensure that stray current effects are detected and mitigated.

10.4.3 The final operating level of a cathodic protection system should be established to achieve the cathodic protection criterion established by the design documents as set forth in Section 4, or by the operating policies of the facility owner.

10.5 Documentation

10.5.1 Documentation of all operating parameters should be completed after the system is energized. Those parameters should include:

- (a) Initial baseline data
- (b) As-built drawings

- (c) Operating currents
- (d) Locations of test facilities
- (e) Key monitoring locations
- (f) Equipment manuals
- (g) Tank fluid level

10.5.2 All collected data should be recorded and documented for future reference.

10.6 Error Sources: Consideration must be given to sources of error when potential readings are made on aboveground storage tank (AST) bottoms. Some of these error sources include:

10.6.1 Measurement Circuit IR Drop: The soil or fill under a tank bottom can be dry and have a high electrolyte resistance. Under these conditions, an IR drop error occurs in the measuring circuit if a low-input impedance meter is used. This error can be

minimized using a meter with an input impedance greater than 10^6 ohms.

10.6.2 Tank Bottom Flexing: When product level is low, the tank bottom can shift upward, affecting the measurement circuit and changing the area of the tank bottom being monitored. This may result in misleading readings. This error can be minimized by ensuring that there is sufficient product level in the tank during measurements.

10.6.3 Measurements Made from Grade Wall (single-bottom tanks): Potential measurements made from grade are strongly influenced by the potentials at the perimeter of the tank bottom or outside the ringwall (if present). To measure the potentials correctly in the center of the tank bottom, it is necessary to use either a stationary reference electrode, or to have an access tube located under the tank bottom.

Section 11: Operation and Maintenance of Cathodic Protection Systems

11.1 This section recommends procedures and practices for maintaining the effective and efficient operation of cathodic protection systems for on-grade carbon steel storage tank bottoms.

11.2 Monitoring Cathodic Protection Systems

11.2.1 The protection systems shall be monitored to ensure adequate cathodic protection of the tank bottoms in accordance with the criteria set forth in Section 4.

11.2.2 Annual surveys should be conducted to verify that the cathodic protection system is meeting the protection criteria. Making more frequent surveys of the system may be desirable in critically corrosive environments or where highly variable conditions are present. The accuracy of stationary reference electrodes should be evaluated during these surveys. The effectiveness of isolating fittings and continuity bonds should also be evaluated during the periodic surveys.

11.2.3 All sources of impressed current should be checked at bimonthly intervals to ensure effective operation of the system. Current and voltage outputs consistent with previous readings or a satisfactory polarized potential measured at the protected tank bottom surface may each be considered evidence of proper functioning.

11.2.4 Potential testing should consist of a minimum of four equally spaced tests on the external circumference and at least one test at the center of the bottom on tanks of 18-m (60-ft) diameter or less. On tanks greater than 18 m (60 ft) in diameter, eight

equally spaced tests on the external circumference and at least one test at the center of the tank bottom should be the minimum testing requirement.

11.2.4.1 Experience has indicated that on large tanks, potential measurements obtained at the perimeter of the tank may not reflect the actual conditions of the entire tank bottom.

11.2.4.2 Potential measurements may be affected by liquid-level changes inside the tank.

11.2.4.3 The cathodic protection system should be monitored for the existence of any stray current interference from adjacent structures or protection systems.

11.2.5 All cathodic protection systems should be inspected as part of a predictive/preventive maintenance program to minimize in-service failure. Inspections should include a check for electrical shorts, ground connections, meter accuracy, rectifier efficiency, and circuit resistance. Scheduled maintenance should include removing debris at the rectifier openings required for cooling and checking to ensure that all connections are secure and unaffected by corrosion. Maintenance should include inspection of junction boxes, test stations, and other equipment.

11.3 Test equipment used for obtaining cathodic protection data should be checked periodically for accuracy and maintained in good operating condition.

11.4 Corrective action shall be taken if surveys and inspections indicate that the cathodic protection system is

no longer providing adequate protection. These actions include the following:

- (a) Repair, replacement, or adjustment of components of the cathodic protection system
- (b) Addition of supplementary cathodic protection when necessary

(c) Repair, replacement, or adjustment of continuity bonds and continuity devices.

11.5 Care should be exercised to ensure that remedial measures intended to restore or enhance protection do not compromise the integrity of liners or membranes.

Section 12: Recordkeeping

12.1 This section recommends pertinent information that should be recorded and filed for future information and reference.

12.2 Tank information should include, but not be limited to, the information outlined in Paragraph 3.2.

12.3 Design and installation records for cathodic protection systems should be kept, including the following information:

- (a) Design calculations and considerations
- (b) Power source capacity, circuit breakers, panels, etc.
- (c) Number of anodes
- (d) Anode material and expected life
- (e) Anode installation details
- (f) Type, quantity, and location of stationary reference electrodes

- (g) Soil resistivity
- (h) Date of energizing and initial current and voltage settings
- (i) Cost of system
- (j) Fluid level in the tank during survey
- (k) As-built drawings of the installation

12.4 Operation and maintenance records for cathodic protection systems should be kept, including the following information:

- (a) Tabulations of bimonthly readings of impressed current power source
- (b) Reports of periodic or annual inspections
- (c) All adjustments, repairs, and additions
- (d) Costs of maintenance
- (e) Test equipment calibration records

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⁽⁴⁾ U.S. Department of Commerce Clearinghouse, Springfield, VA 22151.

Standard Recommended Practice

Galvanic Anode Cathodic Protection of Internal Submerged Surfaces of Steel Water Storage Tanks

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Revised 2004-11-15
Approved February 1996

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ISBN: 1-5790-189-7
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Foreword

The purpose of this standard recommended practice is to present the procedures and practices used in providing galvanic anode cathodic protection (CP) to the normally submerged steel surfaces inside water storage tanks. This standard provides owners, engineers, and contractors with specific guidelines for the design and installation of these CP systems; methods for determining the effectiveness of these systems; and recommendations for the operation and maintenance of these systems. This standard is applicable to water storage tanks of various sizes used in municipal water supply and fire protection, including elevated tanks and flat-bottom tanks at ground level. Although the general principles outlined in this standard are applicable to all such tanks, the galvanic anode CP system described in this standard may not be practical for relatively large tanks.

This standard was originally prepared in 1996 by NACE Task Group (TG) T-7L-1, a component of Unit Committee T-7L on Cathodic Protection. It was revised in 2004 by TG 284 on Cathodic Protection, Galvanic Anode for Internal Submerged Surfaces of Steel Water Storage Tanks—Review of NACE Standard RP0196, "Galvanic Anode Cathodic Protection of Internal Submerged Surfaces of Steel Water Storage Tanks." TG 284 is administered by Specific Technology Group (STG) 05 on Cathodic/Anodic Protection. It is sponsored by STG 11 on Water Treatment and STG 35 on Pipelines, Tanks, and Well Casings. This standard is issued by NACE under the auspices of STG 05.

In NACE standards, the terms *shall*, *must*, *should*, and *may* are used in accordance with the definitions of these terms in the *NACE Publications Style Manual*, 4th ed., Paragraph 7.4.1.9. *Shall* and *must* are used to state mandatory requirements. The term *should* is used to state something good and is recommended but is not mandatory. The term *may* is used to state something considered optional.

**NACE International
Standard
Recommended Practice**

**Galvanic Anode Cathodic Protection of Internal Submerged
Surfaces of Steel Water Storage Tanks**

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Section 1: General

1.1 This standard presents recommended procedures for using galvanic anodes to apply CP to the internal submerged surfaces of steel tanks used for the storage of potable and nonpotable fresh waters.

1.2 It is recognized that impressed current systems are used extensively for CP of the internal surfaces of water storage tanks; however, this standard addresses only galvanic anode systems. For a description of impressed CP current systems, refer to NACE Standard RP0388.¹

1.3 Natural waters, as used in this standard, include both potable and nonpotable fresh water—including reclaimed water—associated with water supply, irrigation, and fire protection systems.

1.4 The ground level and elevated storage tanks considered in this standard are of welded, bolted, or riveted-steel construction, and include many shapes and sizes.

1.5 CP as described in this standard may be used alone to control corrosion of submerged steel surfaces or may be used as a complement to the protection provided by protective coatings or other procedures.² CP cannot protect surfaces that are not submerged; these surfaces must be protected by coatings alone.

1.6 CP may be installed to control corrosion in both newly constructed and existing tanks. When CP is used on

existing tanks, it may be necessary to drain the tank during installation.

1.7 It is recognized that the tanks under consideration are often associated with potable water and fire protection systems that may be subject to public health and safety regulations.³ This standard shall not infringe on those regulations. Proper disinfection of the tanks may be required after installation.

1.8 The provisions of this standard should be applied under the direction of a competent corrosion engineer. The term “corrosion engineer,” as used in this standard, refers to a person who, by reason of knowledge of the physical sciences and the principles of engineering and mathematics as acquired by professional education and related practical experience, is qualified to practice corrosion control, including CP, for water storage tanks. Such persons may be Registered Professional Engineers or persons recognized as being qualified or certified as Corrosion Specialists or CP Specialists by NACE if their professional activities include suitable experience in corrosion control and CP.

1.9 This standard may not be applicable in all situations. The corrosion engineer may consider alternative corrosion control methods.

Section 2: Definitions

Anode: The electrode of an electrochemical cell at which oxidation occurs. Electrons flow away from the anode in the external circuit. Corrosion usually occurs and metal ions enter the solution at the anode.

Anode Circuit: The path from a single anode or multiple anodes connected through a shunt, a resistor, and the connection to the tank.

Calcareous Coating: A layer consisting of calcium carbonate and other salts deposited on the surface. When the surface is cathodically polarized as in CP, this layer is the result of the increased pH adjacent to the protected surface.

Cathode: The electrode of an electrochemical cell at which reduction is the principal reaction. Electrons flow toward the cathode in the external circuit.

Cathodic Protection (CP): A technique to reduce the corrosion of a metal surface by making that surface the cathode of an electrochemical cell.

Cathodic Protection (CP) Coupon: A metal specimen made of similar material as the structure under investigation, which is connected to the external surface of, and immersed in, the electrolyte adjacent to the structure being protected by CP.

Coating: A liquid, liquefiable, or mastic composition that, after application to a surface, is converted into a solid protective, decorative, or functional adherent film.

Conductivity: (1) A measure of the ability of a material to conduct an electric charge. It is the reciprocal of resistivity. (2) The current transferred across a material (e.g., coating) per unit potential gradient.

Corrosion: The deterioration of a material, usually a metal, that results from a reaction with its environment.

Current Density: The current to or from a unit area of an electrode surface.

Driving Voltage: The potential difference between the galvanic anodes and the tank wall when the CP system is in operation.

Electrode: A conductor used to establish contact with an electrolyte and through which current is transferred to or from an electrolyte.

Electrode Potential: The potential of an electrode in an electrolyte as measured against a reference electrode. (The electrode potential does not include any resistance losses in potential in either the electrolyte or the external circuit. It represents the reversible work to move a unit of charge from the electrode surface through the electrolyte to the reference electrode.)

Electrolyte: A chemical substance containing ions that migrate in an electric field. For the purpose of this standard, electrolyte refers to the water, including the dissolved chemicals, in the tank.

Galvanic Anode: A metal that provides sacrificial protection to another metal that is more noble when electrically coupled in an electrolyte. This type of anode is the electron source in one type of CP.

Holiday: A discontinuity in a protective coating that exposes unprotected surface to the environment. For the purpose of this standard, it is a bare spot in a coating that exposes tank internal metal surface to the stored water.

Impressed Current: An electric current supplied by a device employing a power source that is external to the electrode system. (An example is direct current for CP.)

IR Drop: The voltage across a resistance in accordance with Ohm's law.

Polarization: The change from the open-circuit potential as a result of current across the electrode/electrolyte interface.

Polarized Potential: The potential across the structure/electrolyte interface that is the sum of the corrosion potential and the cathodic polarization.

Reference Electrode: An electrode whose open-circuit potential is constant under similar conditions of measurement, which is used for measuring the relative potentials of other electrodes.

Resistivity: (1) The resistance per unit length of a substance with uniform cross section. (2) A measure of the ability of an electrolyte (e.g., soil) to resist the flow of electric charge (e.g., CP current). Resistivity data are used to design a groundbed for a CP system. For the purpose of this standard, resistivity is a measure of the ability of the water to resist the flow of current. Water resistivity is used in the design of the galvanic anode CP system.

Shielding: (1) Protecting; protective cover against mechanical damage. (2) Preventing or diverting CP protection current from its natural path.

Tank-to-Water Potential: The voltage difference between a submerged metallic portion of the tank and the water (electrolyte), which is measured with a reference electrode in contact with the water.

Section 3: Determination of Need for CP

3.1 Introduction

3.1.1 Steel tank surfaces submerged in natural waters are subject to corrosion. The methods and procedures used to control corrosion should be governed by the rate of corrosion and the cost of maintaining the tank, including the water quality and planned useful life of the tank.

3.1.2 Corrosion control by use of coatings alone is possible only if the coating is continuously maintained to provide complete coverage of the surface to be protected. All coatings are subject to damage and deterioration. CP may not be effective under disbonded coating.

3.1.3 CP is effective in controlling corrosion only on submerged metal surfaces during submersion. It does not reverse structural damage already caused by corrosion.

3.2 Coated Steel Tanks

3.2.1 CP should be used to prevent corrosion on submerged, coated steel tank surfaces where holidays exist—or are anticipated—and where corrosion would occur as a result of those holidays.

3.2.2 If the water is sufficiently corrosive to justify the use of a coating, then CP is also justified and provides a greater degree of protection than when either method is used alone.

3.2.3 Properly designed and maintained CP systems extend the useful life of those coatings that are compatible with CP.

3.2.4 The current required for CP is much lower for coated steel tanks compared with bare or poorly coated steel tanks.

3.3 Uncoated Steel Tanks

3.3.1 It is feasible to design a CP system to provide complete protection for uncoated submerged surfaces of steel tanks (see Section 4).

3.3.2 It may be more practical to protect a bare or poorly coated steel tank with an impressed current system. This method is described in NACE Standard RP0388.¹

3.4 Economic Considerations

3.4.1 For coated steel tanks, the cost of CP should be compared with the cost of recoating and metal loss. In addition to extending the life of existing coatings, CP reduces the need for recoating, repairs, leakage, and

replacement caused by metal loss at holidays in the coating.

3.4.2 Metal loss can be reduced by the application of CP where the submerged surfaces are not coated or where the coating has deteriorated to the point that these surfaces can be considered uncoated. The cost of installing CP, projected maintenance costs, and monitoring costs should be compared with the cost of coating maintenance, metal loss, service disruption, reduction in tank life, and water quality degradation.

3.5 Operational Considerations

3.5.1 Removing the tank from service for coating maintenance or repairing corrosion damage can be eliminated or postponed if the CP system is designed and operated properly.

Section 4: Design of Galvanic Anode CP Systems

4.1 General

4.1.1 The elements that the corrosion engineer must consider when designing galvanic anode CP systems for steel water storage tanks are outlined in this section.

4.1.2 In the design of a galvanic anode system, the following items must be considered:

- (a) Health and safety,
- (b) Compliance with local and national regulations,³
- (c) Design of the tank (accessibility, crevices, shielded areas, baffles, and compartments),
- (d) Present and future condition of the coating and the generic type of coating employed,
- (e) Whether the water is subject to freezing,
- (f) Driving voltage of various galvanic anode materials,
- (g) Galvanic anode material, configuration, and circuit resistance,
- (h) Galvanic anode life and ease of replacement,
- (i) Ancillary equipment,
- (j) Reference electrode location(s),
- (k) Possibility of vandalism, and
- (l) Water chemistry and temperature.

4.1.3 Whenever possible, the design should be based on standard galvanic anode shapes and sizes.

4.1.4 Selection of materials and system design shall strive to provide the best economic balance between the installation cost and the maintenance cost over the design life of the system.

4.2 Design Information

4.2.1 Before a galvanic anode CP system is designed, the following information should be obtained:

- (a) Dimensions of the tank, including inlet/outlet columns, if any,
- (b) Area of continuously and intermittently submerged steel surfaces,
- (c) Flow patterns, recirculation, and the presence and design of internal heaters and baffling,
- (d) Chemical analysis of the water and variation with seasons,
- (e) Conductivity range, pH, and velocity of water,
- (f) Frequency and rate of emptying and filling the tank,
- (g) Type, condition, and age of internal coating system,
- (h) Condition of internal steel surfaces exposed to the water,
- (i) Whether the water is subject to freezing,
- (j) Water temperature range, and

(k) Other pertinent information, including age and history of the tank, and whether the tank is of welded, bolted, or riveted construction.

4.2.2 In most cases, an on-site corrosion evaluation and preliminary design survey is useful.

4.3 Design Considerations

4.3.1 Current Output

4.3.1.1 The galvanic anode CP system must be capable of providing sufficient current to protect the tank to the minimum criterion for the full design life of the system, including any anticipated coating deterioration.

4.3.1.2 Calculated current output should be based on the current requirement for CP. This current requirement is expressed in terms of current per unit area of total submerged bare surface area, and depends on the corrosiveness of the water. In fresh waters, the current requirement is usually between 5 and 27 mA/m² (0.5 and 2.5 mA/ft²) of submerged bare surface area. Installations involving high corrosion rates, nonpotable water, and galvanic metal couples may require considerably higher current densities.

4.3.1.3 The driving voltage used with the circuit resistance to calculate the current output shall be the difference between the open-circuit potential of the anode and the minimum polarized potential of the tank.

4.3.1.4 For circuit resistance calculations, refer to *Anode Resistance Fundamentals and Applications—Classic Papers and Reviews*.⁴

4.3.1.5 Circuit resistance variation as a result of temperature and water conductivity changes must be considered. Maximum circuit resistance shall be calculated based on the physical shape of the galvanic anode when it is 85% consumed.

4.3.2 Galvanic Anode Selection

4.3.2.1 Galvanic anodes shall be manufactured from magnesium (Mg) or zinc (Zn) alloys that are formulated specifically for this use. Table 1 lists typical galvanic anode materials and characteristics.

4.3.2.2 Galvanic anode materials shall be chosen to be compatible with the water composition and intended use.

4.3.2.3 All galvanic anodes shall have a steel core that extends throughout the full length of the anode and is centered in the galvanic anode, and on which the anode can be supported either vertically or horizontally.

4.3.3 Galvanic Anode Arrangement

4.3.3.1 Galvanic anodes shall be arranged to provide as close to uniform current density as is practical. When uniform current density cannot be achieved, the total system current output must be increased to compensate by adding anodes or adjusting the system current output through the test box described in Paragraph 4.3.4.1.

4.3.3.2 Galvanic anodes shall be suspended or mounted in such a way as to minimize damage to the system when ice conditions are anticipated or measures must be taken to prevent ice formation.

4.3.3.3 Galvanic anodes shall be installed and supported to prevent damage during high flow rates and when the tank is drained for inspection and cleaning.

4.3.3.4 Note: Some coatings have been damaged by excessive current density at coating holidays and excessive potential gradients across the coating. The coating selected shall be compatible with CP. Coating failures have been observed at polarized potentials more negative than -1,100 mV vs. saturated copper/copper sulfate reference electrode (CSE).

4.3.4 Installation, Monitoring, and Testing

4.3.4.1 One preferred method of installation is to use galvanic anodes with lead wires that connect to a collector (header) cable terminating in a test box with a tank connection cable, a tank test lead, a shunt, and a reference electrode lead. The use of a calibrated shunt between the anode collector cable and the tank connection cable facilitates measuring the current output of the system. The test box allows for interrupting and adjusting the current and obtaining a polarized potential vs. the reference electrode, free of IR drop. Although the other reference electrodes are sometimes used, CSE is preferred.

4.3.4.2 If the galvanic anodes are directly connected to the tank, a coupon and reference electrode shall be configured to evaluate the IR drop and approximate the polarized potential of the tank.⁵

4.3.5 Galvanic Anode Life

4.3.5.1 Galvanic anode life shall be calculated using the nominal operating current density.

4.3.5.2 Galvanic anode current capacities used in the system life calculations for any galvanic anode shall not exceed the consumption rate values given in Table 1.

4.3.5.3 The galvanic anode utilization factor when calculating life shall not exceed 85%.

TABLE 1
TYPICAL GALVANIC ANODE MATERIALS AND CHARACTERISTICS

TYPE	ALLOY	NOMINAL CORROSION POTENTIAL ^(A) mV vs. CSE ^(B)	NOMINAL CONSUMPTION RATE ^(C) kg/A-yr
Mg	ASTM^(D) B 843^(E)		
Mg/Mn	M1C	-1,750	8
Mg/Al/Zn	AZ31B	-1,550	8
Mg/Al/Zn	AZ63B	-1,550	8
Zn	ASTM B 418^(F)		
Low Fe	Type II	-1,100	12

^(A) Corrosion potential varies with water chemistry.

^(B) CSE = Saturated copper/copper sulfate reference electrode.

^(C) Consumption rate is dependent on water chemistry and anode current density.

^(D) ASTM International, 100 Barr Harbor Dr., West Conshohocken, PA 19428-2959.

^(E) ASTM B 843 (latest revision), "Standard Specification for Magnesium Alloy Anodes for Cathodic Protection" (West Conshohocken, PA: ASTM).

^(F) ASTM B 418 (latest revision), "Standard Specification for Cast and Wrought Galvanic Zinc Anodes" (West Conshohocken, PA: ASTM).

4.3.6 Other

4.3.6.1 The preferred method of cable connection to the tank is by welding or thermite welding. If other connection methods, such as bolting, clamping, etc., are used, they must be secure. All electrical connections must be protected against corrosion.

4.3.6.2 All cable connections to the galvanic anodes shall be made to the core material by silver solder and subsequently coated.

4.3.6.3 All immersed cable-to-cable connections shall be made by high-strength compression connector or welding.

4.3.6.4 All cables located inside the tank shall be rated for use in submerged conditions.

4.3.6.5 For bolted and riveted tanks, electrical continuity of all joining components must be achieved if these components are to receive CP.

Section 5: Installation of Galvanic Anode CP Systems

5.1 Introduction

5.1.1 This section outlines installation techniques for galvanic anode CP systems that protect water storage tanks when design considerations recommended in Section 4 have been followed.

5.2 Construction Specifications

5.2.1 All construction work on galvanic anode CP systems should be in accordance with construction drawings and specifications.

5.3 Construction Supervision

5.3.1 All construction work should be performed by, or under the direction of, a person who is qualified by experience in the installation of galvanic anode CP systems in water storage tanks, and who should verify

that the installation is made in accordance with the drawings and specifications.

5.3.2 Deviations from construction documents and specifications shall be noted on as-built drawings and specifications.

5.4 Inspection and Handling

5.4.1 Galvanic anodes shall be inspected for conformance to specifications for correct galvanic anode material and size, length of lead wire, and method of wire connection. All wire and connections shall be carefully inspected for integrity. Damage to galvanic anode assemblies during handling and installation shall be avoided. If defects are not repaired, the anode must be rejected.

5.4.2 Stationary reference electrodes installed as part of the galvanic anode CP system shall be inspected and tested for conformance to the specifications. The stationary reference electrode shall be tested with reference to an accurate calibrated reference electrode in the electrolyte in which the stationary reference electrode is placed. If a difference in potential exists

between the stationary and test reference electrode, the stationary electrode shall be replaced with one that matches the calibrated portable electrode to within ± 10 mV.

5.5 Installation

5.5.1 Construction practices shall conform to all applicable local and national codes.

5.5.2 Test boxes shall be installed at a location for safe and convenient ground access.

5.5.3 All cables shall be protected from abrasion and sharp objects.

5.5.4 Short circuits shall not exist between the cables and the tank structure or conduit.

5.5.5 The preferred method of galvanic anode installation is to ensure that the anodes are electrically isolated from the tank, except through an accessible electrical connection that can be disconnected for testing of the system.

Section 6: Criteria for CP

6.1 Introduction

6.1.1 The purpose of this section is to list the criteria for CP, which, when complied with, either separately or collectively, indicate that adequate CP of submerged portions of steel water tank interiors has been achieved.

6.2 General

6.2.1 The objective of using galvanic anode CP is to control the corrosion of submerged portions of steel water tank interiors.

6.2.2 The selection of a particular criterion for achieving the objective in Paragraph 6.2.1 depends, in part, on prior experience with similar structures and environments wherein the criterion has been used successfully.

6.2.3 The criteria in Paragraph 6.3 were developed through laboratory experiment or were determined empirically by evaluating data obtained from successfully operated CP systems. It is not intended that persons responsible for corrosion control be limited to these criteria if it can be demonstrated by other means that the control of corrosion has been achieved.

6.2.4 Extended periods of time can be required to achieve polarization of uncoated or poorly coated tanks.

6.3 Criteria for Steel Water Tanks

6.3.1 A negative polarized tank-to-water potential of at least 850 mV relative to a CSE.

OR

6.3.2 A minimum of 100 mV of cathodic polarization between the structure surface and a stable reference electrode contacting the electrolyte. The formation or decay of polarization can be measured to satisfy this criterion.

CAUTIONARY NOTE: This criterion is only applicable to steel water tanks not having corrosion cells caused by connection to more noble metals such as copper, brass, or passive stainless steel (e.g., heated water tanks wherein the submerged heater tube is of copper or brass materials and is electrically continuous with the submerged metal of the tank).

6.4 Measurement Procedures

6.4.1 Potential measurements on water tank interiors should be made with the reference electrode located in the water (electrolyte) as close as possible to the tank steel surface. Consideration shall be given to voltage

(IR) drops other than those across the tank/water boundary, the presence of dissimilar metals, structural components, and other conditions that may interfere with valid interpretation of potential measurements.

6.4.2 In order to observe the polarized tank-to-water potential, the IR drop shall be eliminated from the measurement. Among the methods used to eliminate IR drop are (1) measuring the tank-to-water potential with the protective current instantaneously interrupted and (2) interrupting the electrical connection between the tank and a submerged coupon(s) and immediately measuring the tank-to-water potential of the coupon.

6.4.3 A sufficient number of potential measurements shall be taken to determine that adequate protection is being achieved throughout the steel tank, especially at the most difficult-to-protect locations. In practice, potential profiles of the submerged steel at intervals along the wall and floor during initial adjustment shall be taken.

6.5 Alternative Reference Electrodes

6.5.1 While CSE is the standard reference electrode for use in water storage tanks, other reference electrodes that may be substituted for CSE are listed below along with their potential equivalent to -850 mV vs. a CSE.

- (a) vs. Zn: +250 mV, and
- (b) vs. saturated silver/silver chloride electrode: -735 mV.

Regular calibration of reference electrodes is recommended.

6.6 Special Considerations

6.6.1 Abnormal conditions in which protection is ineffective or only partially effective sometimes exist. Such conditions include elevated temperatures, disbonded coatings, shielding, bacterial attack, and unusual contaminants in the water.

Section 7: Operation and Maintenance

7.1 This section covers the procedures necessary for the operation and maintenance of an effective galvanic anode CP system.

7.2 Operation

7.2.1 After the system has been allowed to reach a stable polarization level, the system shall be tested and adjusted to obtain the potentials indicated in Paragraph 6.3.

7.2.2 For a galvanic anode CP system to control corrosion effectively, it must be kept in continuous operation and provide the desired tank-to-water potential.

7.3 Maintenance

7.3.1 Maintenance should be conducted under the direction of qualified personnel as described in Paragraph 1.8 of this standard.

7.3.2 Annual Testing

7.3.2.1 Under normal conditions, testing of galvanic anode systems shall be performed annually. This frequency could vary depending on changes in parameters listed in Paragraph 4.2.1.

7.3.2.2 Tests shall be conducted to determine whether the criteria set forth in Paragraph 6.3 are being achieved. The potential and current output shall be monitored and the circuit resistance

adjusted so that the criteria in Paragraph 6.3 are achieved.

7.3.2.3 Reference Electrodes

7.3.2.3.1 With current off, stationary reference electrodes installed in the tank should be compared with a recently calibrated portable electrode of identical composition to ensure proper levels of protection. If it is not possible to interrupt the current, the stationary reference electrode shall be removed from the tank and tested in a nonmetallic container. The two reference electrodes should have a potential difference of less than ± 10 mV. When the potential difference exceeds ± 20 mV, the stationary electrode shall be replaced.

7.3.2.3.2 Placement of the stationary reference electrode in the tank shall be evaluated to determine whether it corresponds to the most representative of portable reference electrode potentials of the tank. Readings made with a portable reference electrode moved to several different locations shall be compared with readings from the stationary reference electrode to ensure the stationary reference electrode values are representative of the entire tank.

7.3.2.3.3 For installations in which a stationary reference electrode is not installed or is not functioning, a calibrated portable

reference electrode shall be used to take readings at several locations in the tank.

7.3.2.4 Annual Inspections

7.3.2.4.1 All galvanic anode CP system components should be completely inspected annually. The inspection shall include polarized potential measurements—corrected for IR drop by either interruption of the anode current or the coupon connection to the tank—to ensure that the system is operating properly. For tanks with handholes in the top, this includes lowering a portable reference electrode into the tank and taking instant-off measurements along the tank wall to evaluate whether all surfaces of the tank are protected. When instant-off measurements are not possible, the coupon data or some other method shall be used to correct for IR drop. The connection to the portable reference electrode and all the metal components on the electrode and the wire shall be completely insulated.

7.4 Anode Replacement

7.4.1 All galvanic anodes that have ceased to function properly should be replaced. Tank-to-water potentials, current output, and/or visual inspections shall be used to evaluate anode performance.

7.4.2 Damaged or deteriorated cables, anode lead wires, and electrical connections shall be replaced or repaired using specific system components compatible with the original design.

7.4.3 In tanks subject to icing conditions, galvanic anodes shall be inspected and/or tested after the probability for freezing has passed. Damaged anodes shall be replaced.

7.4.4 When the water storage tank is taken out of service, the galvanic anodes should be examined and broken or damaged anodes shall be replaced.

7.4.5 Galvanic anodes should also be examined to determine consumption. When galvanic anode remaining life is less than the time to the next inspection, anodes should be scheduled for replacement.

7.5 Records

7.5.1 Tank Information

7.5.1.1 Complete information and the history of the tank itself should be recorded, including:

- (a) Dimensions and capacity,
- (b) Tank erection and CP contractor,

- (c) Date of erection,
- (d) Coupon type, configuration, and location,
- (e) Original coating, including system, surface preparation, and materials,
- (f) Subsequent coatings and dates of coating,
- (g) History of any structural repairs,
- (h) Costs associated with maintenance of the tank,
- (i) Tank location,
- (j) Warranty dates on coatings and CP, and
- (k) Water temperature range.

7.5.2 Water Information

7.5.2.1 Complete information about the water stored in the tank should be recorded. This information includes both the chemical and electrical characteristics, as well as information about the variations in these characteristics that occur throughout the year. If different sources of water that have substantially different resistances are used, the frequency of maintenance testing may need to be adjusted so that tests are conducted at each time a change in water chemistry occurs. Basic to determining the changes in chemistry would be the resistivity of the water, which can also be reflected by the total dissolved solids in the water.

7.5.2.2 Operational information about frequency of draining, cleaning, and filling should be recorded.

7.5.3 CP

7.5.3.1 Complete information about the installation and design of the galvanic anode CP system should be documented, including:

- (a) The number and configuration of galvanic anodes,
- (b) Galvanic anode dimensions and typical composition,
- (c) Stationary reference electrode type, model number, and manufacturer,
- (d) Wiring and anode suspension,
- (e) Electrical schematic diagrams,
- (f) Individual galvanic anode circuits and shunt resistances,

- (g) Test box with shutoff switch, and
- (h) Date of energizing and initial current and potential readings.

7.5.3.2 Maintenance records that include the following should be kept:

- (a) Tabulation of annual measurements of galvanic anode output voltage and current and tank-to-water potentials. These measurements should be taken when the tank is relatively full.

The water surface elevation should be recorded each time potential measurements are taken. The location of potential measurements should be recorded.

- (b) Reports on annual inspections.
- (c) All repairs and additions to the galvanic anode CP systems.
- (d) Costs of maintenance including coating, CP inspections, etc.

References

1. NACE Standard RP0388 (latest revision), "Impressed Current Cathodic Protection of Internal Submerged Surfaces of Carbon Steel Water Storage Tanks" (Houston, TX: NACE).
2. J.B. Bushman, D.H. Kroon, "Cathodic Protection of Water Storage Tanks," AWWA⁽¹⁾ Journal 76, 1 (1984).
3. ANSI⁽²⁾/NSF⁽³⁾ 61, "Drinking Water System Components—Health Effects" (Ann Arbor, MI: NSF International).
4. R.L. Benedict, ed., Anode Resistance Fundamentals and Applications—Classic Papers and Reviews (Houston, TX: NACE, 1986).
5. NACE Publication 35201 (latest revision), "Technical Report on the Application and Interpretation of Data from External Coupons Used in the Evaluation of Cathodically Protected Metallic Structures" (Houston, TX: NACE).

⁽¹⁾ American Water Works Association (AWWA), 6666 W. Quincy Avenue, Denver, CO 80235.

⁽²⁾ American National Standards Institute (ANSI), 1819 L Street NW, Washington, DC 20036.

⁽³⁾ NSF International (NSF), P.O. Box 130140, 789 Dixboro Road, Ann Arbor, MI 48113-0140.

Standard Recommended Practice

Impressed Current Cathodic Protection of Reinforcing Steel in Atmospherically Exposed Concrete Structures

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Revised 2000-06-16
Approved April 1990
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ISBN 1-57590-103-X
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Foreword

The purpose of this NACE standard recommended practice is to present guidelines for impressed current cathodic protection of reinforcing steel in atmospherically exposed concrete structures. These guidelines provide the design engineer with information to control corrosion of conventional reinforcing steel in portland cement concrete structures through the application of impressed current cathodic protection.

For more information on design, maintenance, and rehabilitation of reinforcing steel in concrete, refer to NACE Standard RP0187¹ and NACE Standard RP0390.² For a state-of-the-art overview regarding the use of reference electrodes for atmospherically exposed reinforced concrete structures, refer to NACE International Publication 11100.³ For a state-of-the-art overview on criteria for cathodic protection of prestressed concrete structures, refer to work in progress by Task Group T-11-1d.⁴

This standard was originally prepared in 1990 by NACE Task Group T-3K-2, a component of Unit Committee T-3K on Corrosion and Other Deterioration Phenomena Associated with Concrete. It was revised by Work Group T-11-1a (formerly T-3K-2) in 2000 and is published by NACE International under the auspices of Group Committee T-11 on Corrosion and Deterioration of the Infrastructure.

To provide for the necessary expertise on all aspects of the subject and to provide input from all interested parties, Task Group T-11-1 was composed of corrosion consultants, consulting engineers, architect-engineers, cathodic protection engineers, researchers, structure owners, and representatives from both industry and government.

In NACE standards, the terms *shall*, *must*, *should*, and *may* are used in accordance with the definitions of these terms in the *NACE Publications Style Manual*, 3rd ed., Paragraph 8.4.1.8. *Shall* and *must* are used to state mandatory requirements. *Should* is used to state that which is considered good and is recommended but is not absolutely mandatory. *May* is used to state that which is considered optional.

**NACE International
Standard
Recommended Practice**

**Impressed Current Cathodic Protection of Reinforcing
Steel in Atmospherically Exposed Concrete Structures**

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Section 1: General

1.1 Background

1.1.1 Reinforcing steel is compatible with concrete because of similar coefficients of thermal expansion and because concrete normally provides the steel with excellent corrosion protection. The corrosion protection is the result of the highly alkaline portland cement that allows a stable, corrosion-mitigating passive oxide film to form and be maintained on the surface of the encased steel. If the film does not form, or is weakened or destroyed so that it does not protect the steel, corrosion can occur. The protective oxide film does not form or is destroyed if (1) excessive amounts of chloride or other aggressive ions are present, (2) alkalinity is lost by reaction with aggressive gases, or (3) the concrete does not fully encase the steel.

1.1.2 Corrosion occurs as a result of the formation of an electrochemical cell. An electrochemical cell consists of four components: an anode, where oxidation occurs; a cathode, where reduction occurs; a metallic path, where the electric current is electron flow; and an electrolyte (concrete), where the electric current is ion flow in an aqueous medium. The anodic and cathodic areas occur as a result of coupling dissimilar metals and/or exposure to differential environmental conditions. If any one of the four elements of the electrochemical cell is eliminated, corrosion can be prevented.

1.2 Cathodic Protection

1.2.1 The basic principles of corrosion can be used to understand the theory of cathodic protection. Cathodic protection is defined as a technique to reduce the corrosion of a metal surface by making that surface the cathode of an electrochemical cell.

1.2.2 Cathodic protection is a proven technique for controlling corrosion of steel in existing chloride-contaminated concrete structures. However, cathodic protection will neither replace lost steel nor return corroded reinforcement to its original section. There may be areas of the reinforced concrete structure that appear sound by traditional inspection techniques that are, in fact, corroding and experiencing corrosion-related tensile stress near the rupture levels. Such distressed areas may crack, spall, or delaminate subsequent to the application of cathodic protection.

NOTE: For further information, see a glossary of terms in Appendix A.

1.3 Scope and Limitations

1.3.1 The provisions of this standard should be applied under the direction of a registered Professional Engineer or a person certified by NACE International as a Corrosion Specialist or certified as a Cathodic Protection Specialist. The person's professional experience should include suitable experience in cathodic protection of reinforced concrete structures. Under certain circumstances, a cathodic protection system may either become a structural component or significantly affect the serviceability and structural performance of a reinforced concrete structure; therefore, review of such impact by the cathodic protection system should be made by a qualified registered Structural Engineer or the equivalent.

1.3.2 The guidelines presented here are limited to impressed current cathodic protection systems for new or existing atmospherically exposed reinforced concrete and are not applicable to prestressed concrete.

Section 2: Criteria

2.1 The criteria in this section serve as a guide for achieving cathodic protection and providing corrosion control for reinforcing steel embedded in atmospherically exposed concrete. Compliance with these criteria is dependent on analysis of representative data in each situation. These criteria are applicable only with impressed current systems. The number and locations of measurements made during data collection should be commensurate with the complexity of the structure being protected. Sampling plans should be in accordance with

ASTM⁽¹⁾ E 105.⁵ Sample size should be determined in accordance with ANSI⁽²⁾/ASQC⁽³⁾ Z1.4,⁶ with the unit of product typically being 0.836 m² (1.00 yd²) of protected metal surface area. For structures in which cathodic protection systems are divided into discrete zones, testing inspection lots should be defined. Acceptable quality and confidence levels should also be defined. Potentials of reinforcing steel or other embedments measured against portable reference electrodes shall be obtained in accordance with the techniques described in ASTM C 876.⁷

⁽¹⁾ American Society for Testing and Materials (ASTM), 100 Barr Harbor Dr., West Conshohocken, PA 19428-2959.

⁽²⁾ American National Standards Institute (ANSI), 11 W. 42nd St., New York, NY 10036.

⁽³⁾ American Society for Quality (ASQ), 611 East Wisconsin Ave., Milwaukee, WI 53201-3005.

Sign conventions for potential and current density as well as conventions for graphical presentation of data should be in accordance with ASTM G 3.⁸

2.2 Situations in which physical conditions effectively preclude full implementation of sampling programs derived from ASTM E 105 and ANSI/ASQC Z1.4 may exist. Examples of these cases include asphalt or other nonconductive overlays, conductive asphalt cathodic protection systems, and situations in which access to the cathodically protected surface is difficult and limited. In these situations embedded reference electrodes should be installed. Additionally, “most anodic” sites may be constructed. Typically, this involves fully exposing a short length of existing reinforcement. The excavation is then patched with concrete containing an amount of chloride well above that found in existing conditions. Attention should be given to the location of “most anodic” sites to avoid making the sites exceptionally favorable cathodic protection current paths. A reference electrode may also be installed. It is important that the reinforcing steel adjacent to the embedded reference electrode be left in the original concrete. If this is not done, the measured potentials will not be representative of the reinforcing steel in undisturbed concrete. If “most anodic” sites are to be the basis for cathodic protection system performance judgment, the number of sites constructed should reflect the complexity of the structure.

2.3 NACE Work Group T-11-1a developed these criteria through empirical evaluation of data obtained from successfully operated impressed current cathodic protection systems. NOTE: Persons using this standard should review data made available after this standard's publication to determine whether more effective criteria have been established. It is not intended that persons responsible for corrosion control be limited to these criteria if it can be demonstrated by other means that corrosion control has been achieved. A combination of criteria may be used for a single structure.

2.3.1 100-mV Polarization Development/Decay

2.3.1.1 A minimum of 100 mV of polarization should be achieved at the most anodic location in each 50 m² (500 ft²) area or zone, or at artificially constructed anodic sites, in accordance with Paragraphs 2.1 and 2.2, provided its corrosion potential or decayed off-potential is more negative than -200 mV_{CSE} (versus a copper/copper sulfate reference electrode [CSE]). If the corrosion potential or decayed off-potential is less negative than -200 mV_{CSE}, then the steel is passivated and no minimum polarization is required.

2.3.1.2 When the polarization decay method is used, the decay should be determined by interrupting the protective current and monitoring the reinforcement's potential measured relative to a stable reference electrode. When the current is interrupted an immediate voltage shift that is the result of eliminating the IR drop occurs. This shift should not be included in the polarization measurement. The potential of the steel immediately after the shift (instant-off potential measured between 0.1 and 1.0 second after interrupting the current flow) shall be used as the initial value from which to measure polarization. Figure 1 depicts a typical polarization decay curve. The polarization equals the instant-off potential subtracted from the reinforcement's final “depolarized potential.”

2.3.1.3 Polarization development should be determined by measuring the potential immediately before applying current to the reinforcing steel and measuring the instant-off potential at intervals of time during the polarization of the steel reinforcement.

The polarization equals the initial reinforcement potential (static potential) before applying current subtracted from the reinforcement's “final instant-off potential.” Figure 2 depicts a typical polarization development curve using “instant-off” values only.

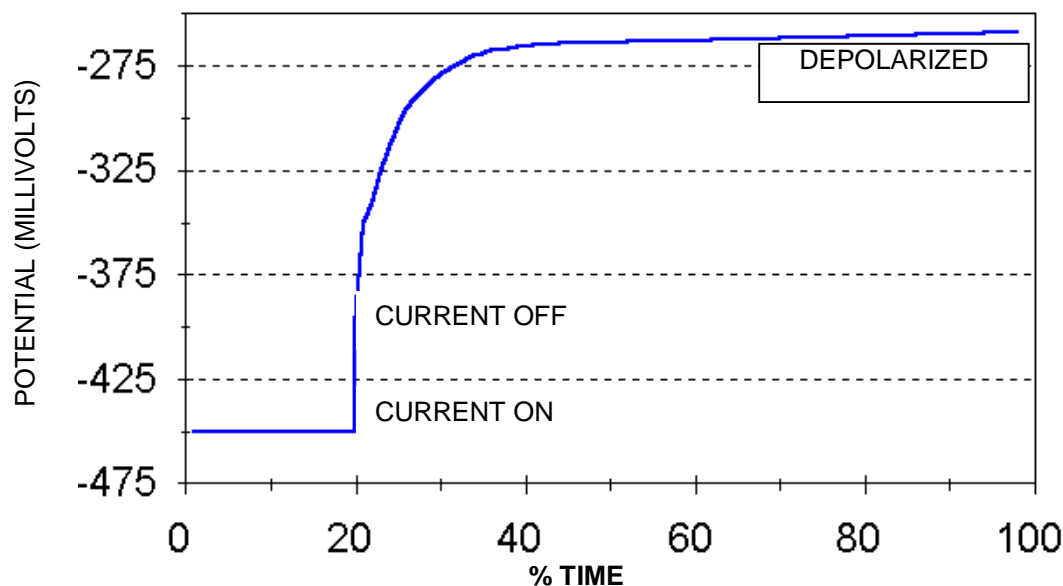


FIGURE 1—Typical Polarization Decay Curve

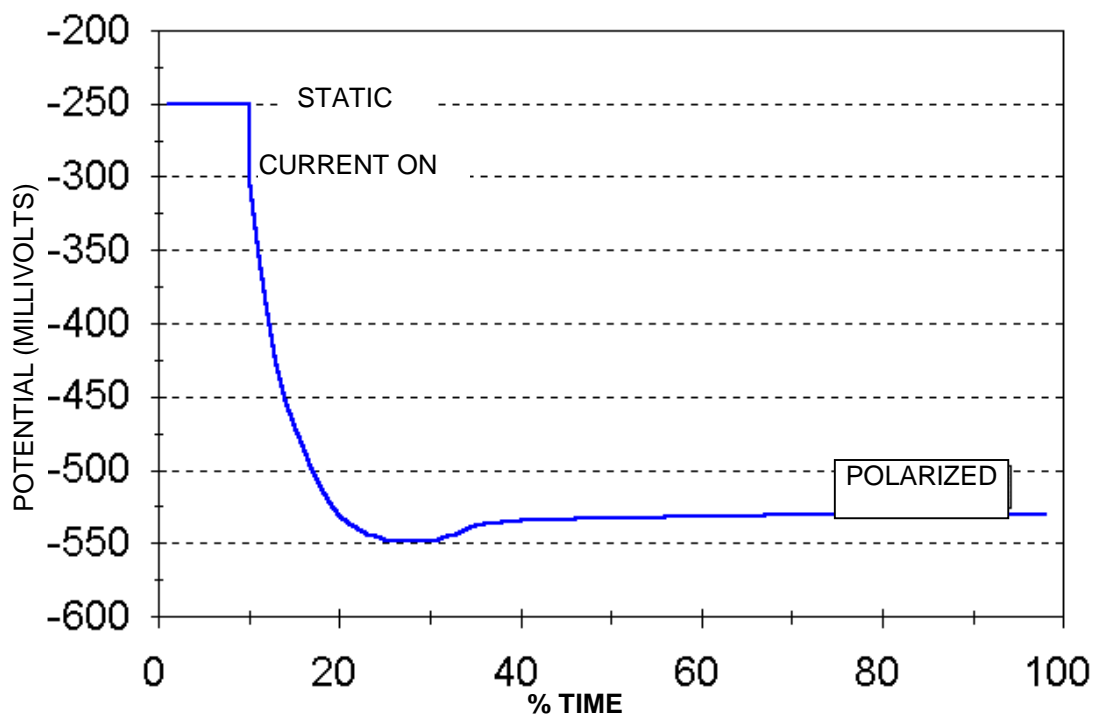


FIGURE 2—Typical Polarization Development Curve Showing “Instant-Off” Potentials Only

2.3.1.4 Changes in environmental conditions such as temperature and moisture can significantly change the native corrosion potential, decayed off-potential, and rate of decay being measured from one day to the next. Therefore, during the polarization measurement interval, the corrosion engineer shall monitor for the impact of these phenomena throughout the test period to ensure

that these conditions have not affected the readings. The period for potential decay or polarization development is largely determined by oxygen availability at the reinforcement surface and is not a reflection of the efficiency of the cathodic protection system. Longer periods of decay or polarization development are required for

less permeable, coated, or water-saturated concrete.

2.3.2 E-log I Test

2.3.2.1 An E-log I test is conducted by application of cathodic current to the steel, followed by measurement of the potential response of the

steel. The results are analyzed graphically after plotting (E) versus the logarithm of the applied current (log I). The use of the E-log I test procedure is subject to the practitioner's interpretation of the data obtained. Consequently, this technique is more often used to determine the initial cathodic protection current requirement.

Section 3: Design of Impressed Current Cathodic Protection Systems

3.1 Introduction

3.1.1 This section provides guidelines for designing impressed current cathodic protection systems that will satisfy the criteria listed in Section 2 and that will exhibit maximum reliability over the intended operating life of the systems.

3.2 Impressed current cathodic protection systems

3.2.1 Impressed current cathodic protection systems consist of anodes and a source of direct current power.

3.2.2 The following types of impressed current cathodic protection system anodes are currently available:

3.2.2.1 Conductive overlays, which consist of conductive materials dispersed in a binder applied to the surface of the concrete structure.

3.2.2.2 Carbon-based conductive coatings applied to the concrete.

3.2.2.3 Thermally sprayed metallic coatings.

3.2.2.4 Conductive materials that are mechanically attached to the concrete structure surface and overlaid with a cementitious material.

3.2.3 Impressed current anodes can be materials such as platinum clad or electroplated on niobium or titanium, conductive polymers, carbon-based or metallic coatings, mixed-metal-oxide coated titanium, conductive grouts, and conductive asphaltic concrete.

3.3 Information useful for selecting and designing an impressed current cathodic protection system includes:

3.3.1 As-built drawings of the concrete structure

3.3.2 Condition survey (in accordance with ACI 201⁹)

3.3.3 Potential survey (in accordance with ASTM C 876)

3.3.4 Chloride analysis of the concrete

3.3.5 Electrical continuity of the embedded metal

3.3.6 Repair and maintenance history

3.3.7 Concrete cover

3.3.8 AC power availability

3.3.9 Concrete resistivity data

NOTE: Some additional information useful for design is included in Appendix B.

3.4 Parameters for selection of the impressed current cathodic protection system

3.4.1 The cathodic protection system shall provide sufficient current to the structure to be protected and distribute this current so that the selected criterion for cathodic protection is attained.

3.4.2 The design life of the cathodic protection system must be commensurate with the required life of the protected concrete structure.

3.4.3 Electrochemical performance of the anodes

3.4.3.1 Anode materials have different rates of consumption when discharging a given current density from the anode surface in a specific environment. Therefore, for a given current density, the anode life depends on the electrochemical properties of the anode material, volume, surface area, and geometry.

3.4.3.2 The system shall be designed to limit the maximum sustained current density at the effective surface contact area between the anode and the concrete to levels below 108 mA/m² (10.0 mA/ft²). Sustained operation at current densities above these levels may result in deterioration of the concrete at the anode-concrete interface.

3.4.3.3 The anode material selected should be resistant to the electrochemical reactions that occur at the anode-concrete interface.

3.4.3.4 Concrete drying effects can limit the ability of the anode to deliver adequate current at specified circuit voltage.

3.4.4 Structural considerations

3.4.4.1 The physical space available, access, maintenance of right-of-way, safety, and other construction and maintenance aspects should be considered. Overhead clearance and dead load constraints may preclude the use of overlay systems in some areas of concrete structures.

3.4.4.2 Future repairs to the concrete structure and future extensions to the cathodic protection system should be considered.

3.4.4.3 The physical properties of anode material selected must be compatible with the concrete structure.

3.4.4.4 Durability, shrinkage, ease of repair and, if relevant, skid resistance of wearing surfaces should be considered in the selection of anode systems.

3.4.4.5 The effect of construction and repair techniques that utilize insulating materials (e.g., epoxy injection), high temperature (e.g., asphaltic overlays), or impact loads should be considered in the selection of anode systems, instrument design, and wiring methods.

3.5 In the design of an impressed current cathodic protection system, the following items should be considered.

3.5.1 Materials and installation practices that conform to applicable codes and standards such as the National Electrical Code¹⁰ issued by the NFPA,⁽⁴⁾ those issued by OSHA,⁽⁵⁾ NEMA,⁽⁶⁾ NACE, ACI,⁽⁷⁾ ASTM, and any other applicable codes or standards should be specified.

3.5.2 Detailed specifications should be given for all materials and installation practices to include transportation, storage, handling, and disposal that are to be incorporated in construction of the impressed current cathodic protection system. When performance specifications or requirements are used, specific evaluation procedures should be outlined or citations published, and recognized industry standards should be listed. Terminology should be clearly defined.

3.5.3 Voltage and current attenuation along the anode and its connecting wire in distributed anode impressed current systems should be evaluated. The design should optimize anode system length, anode spacing and size, and conductor size in order to achieve the criteria set forth in Section 2.

3.5.4 The proximity of anodes to other metallic embedments such as form ties, chairs, tie wire, embedment plates, and electrical conduit shall be determined. Minimum depth of cover over the reinforcement must be maintained in accordance with the manufacturer's recommendations. If the minimum cover cannot be maintained, insulating methods should be used to prevent deadshorts or near shorts in specific areas.

3.5.5 Rectifiers should be selected to provide adequate allowance for anticipated changes in current requirements and circuit resistance with time. Circuit resistance is related to the type of concrete used, internal moisture content, temperature, and chloride content with their respective fluctuations.

3.5.6 Components should be located where the possibility of damage is minimal.

3.5.7 System design shall provide safe step-and-touch potentials.

3.5.8 Suitable design drawings that clearly delineate the overall layout of the concrete structure to be protected should be prepared. The location of significant items of system hardware, corrosion control test stations, electrical bonds, electrical insulators, and adjacent metallic embedments should be shown.

3.5.9 Design or shop drawings, details, and schedules for each impressed current cathodic protection installation should be prepared to show quantities, detailed anode layout, relevant typical cross-sections, and location of the components within the protected concrete structure(s). Tolerances should be stated.

3.5.10 In areas where stray currents are suspected, appropriate tests should be conducted. Special considerations may be required to achieve the criteria set forth in Section 2 when stray currents are encountered.

3.5.11 Cathodic protection may not be appropriate to protect certain metal items mounted on, in, or adjacent to the protected concrete structure. Electrical isolation and avoiding stray current corrosion of such items should be addressed during the cathodic protection system design.

⁽⁴⁾ National Fire Protection Association (NFPA), 1 Battermarch Park, Quincy, MA 02269-9101.

⁽⁵⁾ Occupational Safety and Health Administration (OSHA), 200 Constitution Ave NW, Washington, DC 20210.

⁽⁶⁾ National Electrical Manufacturers Association (NEMA), 1300 N. 17th St. Ste. 1847, Rosslyn, VA 22209.

⁽⁷⁾ American Concrete Institute (ACI), P.O. Box 9094, Farmington Hills, MI 48333.

3.5.12 Redundancy of current output, circuitry, and monitoring components and the capacity to readily isolate sections of the impressed current cathodic

protection system can be beneficial. These features can minimize the area affected by a malfunction or physical damage.

Section 4: Installation Practices

4.1 It is critical for the successful operation of the impressed current cathodic protection system that all materials and equipment be installed according to manufacturer's and design specifications. Installation procedures include intermediate testing, quality assurance of materials, and application restrictions. Materials and installation practices should conform to applicable codes and standards such as the National Electrical Code, those issued by OSHA, NEMA, NACE, ACI, ASTM, and any other applicable codes or standards.

4.2 Quality assurance of materials should be made by acceptance of manufacturer's certification, on-site test, or sample testing in a qualified independent laboratory. Quality assurance requirements should be clearly stated in the design specifications.

4.3 Ongoing inspection and testing shall be conducted throughout construction to ensure that design and manufacturer's specifications are met and recorded.

4.3.1 Electrical continuity or isolation requirements between reinforcing bars and other embedded metals must be verified.

4.3.2 Equipment used for installation shall be in accordance with manufacturer's specifications and any other conditions specified by the material's manufacturer or design specifications.

4.3.3 Pertinent storage and application restrictions should be given in the design specifications. Such restrictions include, but are not limited to, temperature, relative humidity, surface moisture content, and surface preparation.

Section 5: Energizing and System Adjustment

5.1 This section presents recommended procedures for the energizing and adjustment of an impressed current cathodic protection system.

5.2 Component Installation Inspection

5.2.1 Prior to energizing, the AC service to the cathodic protection system shall be inspected for compliance with the National Electrical Code and such local codes and ordinances that may be applicable or in force. It shall be verified that the AC service voltage, phase, and wiring size are compatible with the cathodic protection rectifier.

5.2.2 Prior to energizing, the rectifier shall be inspected. The integrity of all AC input and DC output connections shall be verified. All mechanical fasteners shall be inspected and tightened or replaced if appropriate.

5.2.3 The primary and, if appropriate, secondary anodes, including feed circuitry, shall be visually inspected for proper installation. It shall be established that no short circuits exist between any anode material and any metal embedments.

5.2.4 The electrical continuity between all the steel reinforcement and other metal embedments intended

to be cathodically protected shall be tested at accessible locations.

5.2.5 Electrical isolation of metal mounted on, in, or adjacent to the protected concrete structure and not designed to be cathodically protected should be verified.

5.2.6 All reference and monitoring devices and attendant hardware shall be inspected for proper installation and operation in accordance with the manufacturer's instructions and design specifications. The open-circuit potential of all permanent reference electrodes shall be measured against a closely placed, calibrated, stable portable reference electrode.

5.2.7 Additional cathodic protection equipment and associated components shall be inspected for proper installation and operation in accordance with the manufacturer's instructions and design specifications.

5.3 System Energizing and Adjustment

5.3.1 After completion of the component installation inspection, the impressed current cathodic protection system shall be energized. Each rectifier shall be turned on and operated manually at not more than 20% of the full rated maximum design current output.

During this initial energizing period, all circuits shall be tested.

5.3.1.1 Proper circuit polarity shall be verified.

5.3.1.2 The rectifier shall be tested for proper operation. The accuracy of all rectifier meters shall be verified with a calibrated portable meter.

5.3.1.3 Proper cathodic protection current distribution through all anode feed circuits shall be determined. If panel boards for such testing were not included in the system design, clamp-on DC ammeters or other techniques should be used.

5.3.1.4 The anodes shall be inspected for proper operation. Areas of relatively high initial current discharge shall be investigated.

5.3.1.5 Reference electrodes and other monitoring devices shall be tested.

5.3.1.6 Additional equipment required by the cathodic protection system design shall be inspected for proper operation.

5.3.2 After completion of the initial energizing inspection, the impressed current cathodic protection system should be adjusted for current requirements in accordance with Section 2.

5.3.3 After adjustment, the cathodic protection system should be operated continuously for a period of at least one month before conducting acceptance testing to verify that the operational criterion selected in Section 2 is being met. Environmental or physical extremes can affect system performance and must be considered in acceptance testing.

5.3.4 Tests should be conducted to verify that electrically isolated metal is not adversely affected by stray current from the operation of the impressed current cathodic protection system.

Section 6: Operation and Maintenance of Impressed Current Cathodic Protection Systems

6.1 This section presents recommended procedures and practices for maintaining continuously effective and efficient operation of impressed current cathodic protection systems.

6.1.1 Electrical measurements and inspections are necessary to determine that, once achieved, protection according to the selected criterion is maintained and that each part of the impressed current cathodic protection system is operating properly. Conditions that affect protection are subject to change with time. Corresponding changes may be required in the cathodic protection system to maintain protection. Periodic measurements and inspections are necessary to detect changes in the cathodic protection system. Conditions in which operating experience indicates that testing and inspections need to be made more frequently than recommended herein can exist.

6.1.2 Adequate locations, number, and types of electrical measurements shall be used to determine the effectiveness of cathodic protection.

6.2 All cathodic protection systems should be inspected as part of a preventive maintenance program to minimize in-service failure. Inspections should include a check for electrical shorts, ground connections, meter accuracy, rectifier efficiency, and circuit resistance. Annual surveys should be conducted to verify that the cathodic protection system is meeting the protection criterion. The accuracy of permanent embedded reference electrodes should be evaluated during these surveys. The effectiveness of continuity bonds and isolation of cathodic protection circuits should be evaluated during the periodic surveys. These

surveys should be conducted under the direction of persons described in Section 1 of this standard.

6.3 All sources of impressed current should be checked at intervals of one month or at such intervals as necessary to ensure effective operation of the system. Evidence of proper functioning can be normal current and voltage output, a signal indicating normal operation, or a satisfactory polarized potential state of the embedded steel.

6.4 The test equipment used for obtaining cathodic protection data should be of an appropriate type. Instruments and related equipment should be maintained in good operating condition and checked periodically for accuracy. A list of appropriate test equipment is provided in Appendix C.

6.5 Remedial measures should be taken where annual surveys and inspections indicate that protection is no longer effective. These measures may include the following:

6.5.1 Repair, replace, or adjust components of the cathodic protection system.

6.5.2 Provide supplementary cathodic protection where additional protection is necessary.

6.5.3 Repair, replace, or adjust continuity bonds and defective isolating devices.

6.6 An operations and maintenance manual that includes the following information should be provided.

RP0290-2000

6.6.1 Description of concrete structure and impressed current cathodic protection system.

6.6.2 As-built drawings of cathodic protection system.

6.6.3 Periodic inspection requirements.

6.6.4 System output parameters.

6.6.5 Rectifier maintenance requirements.

6.6.6 System physical maintenance requirements.

6.6.7 Spare parts list.

6.6.8 System reporting records.

6.6.9 Required test procedures.

6.7 A training program should be provided for the owner/operator and should include the necessary information and data required for system operation.

6.7.1 System operation training shall include the following:

6.7.1.1 Adjustment and operation of the rectifier and components.

6.7.1.2 Adjustment of other related components of the cathodic protection system.

6.7.1.3 Evaluation of electrical continuity bonds and effectiveness of electrical isolation.

6.7.1.4 Proper use of other associated components, including reference electrodes and test coupons.

6.7.1.5 Reinforcement and permanent reference electrode potential measurements.

6.7.1.6 Current and voltage measurements.

Section 7: Records

7.1 Records of the cathodic protection system shall be maintained. This provides reference to previously obtained data in the event that changes occur, troubleshooting is required, or modifications or additions are made to the system. These records should include all the physical, design, and test data accumulated on the installation.

7.2 The following information, if collected during the design survey, should be made an integral part of the record.

7.2.1 Results of chloride in concrete tests and other chemical and physical analyses.

7.2.2 Delamination survey data.

7.2.3 Depth-of-cover data.

7.2.4 Reinforcement and permanent reference electrode potential data.

7.2.5 Electrical continuity and electrical isolating data.

7.2.6 Current requirement data.

7.3 During installation of the impressed current cathodic protection system, certain tests should be performed to ensure a quality installation. The following data should be part of the records:

7.3.1 Electrical continuity verification.

7.3.2 Tests for electrical shorts.

7.3.3 Tests for electrical isolation.

7.4 The following additional information, if available, shall be included in the permanent records of the impressed current cathodic protection system:

7.4.1 Tests conducted to determine that all components are in working order prior to permanent energizing.

7.4.2 Reinforcement potential data at representative locations prior to energizing the system.

7.4.3 Reinforcement potential data at representative locations after energizing the system.

7.4.4 Criterion compliance data.

7.4.5 Final rectifier data including voltage and current outputs, mode of control including limits, rectifier serial number, and AC and DC capacity.

7.4.6 Current density and distribution data.

7.5 Detailed as-built drawings and data should be incorporated into the permanent records.

7.6 The operation and maintenance manual shall become a part of the permanent records for the system.

References

1. NACE Standard RP0187 (latest revision), "Design Considerations for Corrosion Control of Reinforcing Steel in Concrete" (Houston, TX: NACE).
2. NACE Standard RP0390 (latest revision), "Maintenance and Rehabilitation Considerations for Corrosion Control of Existing Steel Reinforced Concrete Structures" (Houston, TX: NACE).
3. NACE Publication 11100 (latest revision), "Use of Reference Electrodes for Atmospherically Exposed Reinforced Concrete Structures" (Houston, TX: NACE).
4. Work in Progress by NACE Task Group T-11-1d, "Criteria for Cathodic Protection of Prestressed Concrete Structures" (Houston, TX: NACE).
5. ASTM E 105 (latest revision), "Standard Practice for Probability Sampling of Materials" (West Conshohocken, PA: ASTM).
6. ANSI/ASQC Z1.4 (latest revision), "Sampling Procedures and Tables for Inspection by Attributes" (Milwaukee, WI: ASQC).
7. ASTM C 876 (latest revision), "Test Method for Half-Cell Potentials of Uncoated Reinforcing Steel in Concrete" (West Conshohocken, PA: ASTM).
8. ASTM G 3 (latest revision), "Standard Practice for Conventions Applicable to Electrochemical Measurements in Corrosion Testing" (West Conshohocken, PA: ASTM).
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Appendix A— Glossary of Terms

Attenuation: Electrical losses in a conductor caused by current flow in the conductor.

Cathodic Protection: A technique to reduce the corrosion of a metal surface by making that surface the cathode of an electrochemical cell.

Depolarization: The removal of factors resisting the current in an electrochemical cell.

Design Specifications: A set of documents that, in aggregate, form the nucleus for well-founded, understandable, and equitable contract documents. These documents include written specifications and drawings.

Drying Effect: Migration of water molecules away from the anode as a result of current flow.

Electrical Continuity: A closed circuit (unbroken electrical path) between metal components under consideration.

Electrical Isolation: The condition of being electrically separated from other metallic structures or the environment.

Electrode Potential: The potential of an electrode in an electrolyte as measured against a reference electrode. (The electrode potential does not include any resistance losses in potential in either the electrolyte or the external circuit. It represents the reversible work to move a unit of charge from the electrode surface through the electrolyte to the reference electrode.)

Energizing: The process of initially applying power to turn on an impressed current cathodic protection system.

Immediate Voltage Shift: The difference between the potential value when the power source is on and the instant-off value. (This is also referred to as IR Drop.)

Instant Off Potential: The polarized potential of an electrode with respect to a reference electrode taken immediately after the impressed current flow is stopped (closely approximates the IR-free value when there was current flow).

Overlay: A layer of concrete or mortar placed over and usually bonded onto the worn or cracked surface of a concrete slab to restore or improve the function of the previous surface.

Polarization: The change from the open-circuit potential as a result of current across the electrode/electrolyte interface.

Polarization Decay: The decrease in electrode potential with time resulting from the interruption of applied current.

Potential Survey: Obtaining potentials with respect to a reference electrode at multiple locations on the surface of the concrete structure.

Prestressed Concrete: Concrete in which internal stresses of such magnitude and distribution are introduced that the tensile stresses resulting from the service loads are counteracted to a desired degree; in reinforced concrete the prestress is commonly introduced by tensioning the tendons.

Rectifier: An electrical device for converting alternating current to direct current.

Reference Electrode: An electrode whose open-circuit potential is constant under similar conditions of measurement, which is used for measuring the relative potentials of other electrodes.

Step-and-Touch Potentials: The electrical potential gradients that may exist between two points on the electrolyte surface equal to one pace (one meter) or between a grounded metallic object and a point on the electrolyte surface separated by the distance equal to a human's normal reach (one meter).

Stray Current: Current through paths other than the intended circuit.

Appendix B—Additional Information Useful for Design

1. Site-related:
 - a. Location
 - b. Climate
 - c. Exposure
 - d. Use
 - e. Access
 - f. Environmental factors
 - g. Chloride source
 - h. Possible stray current sources
2. Structure-related:
 - a. Use restrictions
 - b. Design load
 - c. Construction dates
 - d. Repair details and history
 - e. Concrete design properties
 - f. Reinforcing details
 - g. Other embedments
 - h. Overlays, sealers, membranes
 - i. Chloride test and chemical analysis
 - j. Chloride source
 - k. Potential survey
 - l. Delamination survey
 - m. Cover survey
 - n. Continuity of embedded metal
 - o. Existing cathodic protection
 - p. Electrical isolation from foreign structures
 - q. Location and details of joints
 - r. Location and details of drains and scuppers and drainage conditions
 - s. Location and details of railings
 - t. Location of lighting, conduits, and pipes
 - u. Prestressed elements
 - v. Sulfates
 - w. Carbon dioxide
 - x. pH
 - y. Resistivity
3. System-related:
 - a. Circuit resistances
 - b. Power supply rating and location
 - c. Current distribution
 - d. Anode current densities
 - e. Instrumentation for monitoring
 - f. Physical, electrical, and environmental protection of components
 - g. Maintenance interval
 - h. Materials
 - i. Equipment

- j. Electrode reactions
- k. Protective current requirements to meet applicable criteria (see Section 2)
- l. Electrical resistivity of the concrete
- m. Electrical continuity
- n. Electrical isolation
- o. Stray currents
- p. Other maintenance and operating data
- q. Connections and splices
- r. Step-and-touch potentials

Appendix C— Test Equipment

Equipment used for evaluating corrosion and corrosion control of reinforced concrete can include the following:

- 1. pH testing equipment
- 2. Resistivity meter—AC type
- 3. Sulfate and chloride test equipment
- 4. DC voltmeter with variable input impedance
- 5. Multimeter (AC-DC volts, ohms, amps, 10 megohm minimum)
- 6. Portable reference electrodes
- 7. DC source: generator/battery
- 8. Equipment for use during current requirement tests
- 9. Reinforcement depth-of-cover meter
- 10. Metal detector

Standard Recommended Practice Steel-Cased Pipeline Practices

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Approved 2000-01-14
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ISBN 1-57590-094-7
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Foreword

This standard recommended practice details acceptable practices for the design, fabrication, installation, and maintenance of steel-cased metallic pipelines. It is intended for use by personnel in the pipeline industry.

The use of cased carrier pipe for pipelines crossing under highways and railroads is common practice in the industry. The first cased crossings were made using large-diameter pipe. The carrier pipe was mechanically coupled and pushed through the casing, and the coupling or collars were in direct contact with it. When coatings came into general use, isolating spacers were made of hemp rope saturated with pipe-coating enamel. End seals consisting of either concrete or pipe-coating enamel were poured into each end of the casing. The current practice of installing cased carrier pipe has changed only slightly since the beginning of its use. External loading of the carrier pipe has now been eliminated by the installation of heavy-wall casing pipe, and isolating spacers are used to prevent electrical contact between the casing and the carrier pipe. End seals are used to keep mud and water out of the annular space between the carrier pipe and casing.

This standard was prepared by NACE Task Group T-10A-18, a component of Unit Committee T-10A on Cathodic Protection. It is based on NACE Publication 10A192, "State of the Art Report on Cased Pipeline Practices," written by the same task group in 1992. This standard is issued by NACE International under the auspices of Group Committee T-10 on Underground Corrosion Control.

In NACE standards, the terms *shall*, *must*, *should*, and *may* and are used in accordance with the definitions of these terms in the *NACE Publications Style Manual*, 3rd ed., Paragraph 8.4.1.8. *Shall* and *must* are used to state mandatory requirements. *Should* is used to state that which is considered good and is recommended but is not absolutely mandatory. *May* is used to state that which is considered optional.

**NACE International
Standard
Recommended Practice
Steel-Cased Pipeline Practices**

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Section 1: General

1.1 Steel casings are used to install and maintain pipeline crossings such as those at road and railroad rights of way. This standard details acceptable practices for the design, fabrication, installation, and maintenance of steel-cased pipelines.

1.2 Use of cased crossings should be avoided unless required by load considerations, unstable soil conditions, or when their use is dictated by sound engineering practices.

1.3 This standard does not imply that utilization of casings is mandatory or necessary.

1.4 This standard does not imply that cased crossings, whether electrically isolated or electrically shorted, contribute to corrosion of a carrier pipe within a cased crossing. However, cased crossings may adversely affect the integrity of the carrier pipe by shielding CP current to the pipe or reducing the CP effectiveness on the pipe in the vicinity of the casing.

1.5 The practices contained in this standard may or may not be applicable to casings installed prior to its issuance. It is presumed that all practices described in this standard are performed in a safe manner.

Section 2: Definitions

Carrier Pipe: The pipe or piping that goes through the casing or sleeve.

Casing: A metallic pipe (normally steel) installed to contain a pipe or piping.

Dogleg or Doglegged: A term used to describe an offset vent pipe. The vent is offset using several fittings and the shape is similar to a “dog’s leg.”

Electrolytic Contact: Ionic contact between two metallic structures via an electrolyte.

Holiday Testing: Electrical testing of a coating to locate imperfections (holidays).

Isolator or Spacer: A dielectric device specifically designed to electrically isolate a carrier pipe from a casing and provide support for the carrier pipe.

Metallic Short: Direct or indirect metallic contact between two metallic structures.

Split Sleeve: A method of in situ casing installation by welding two halves of the casing (split sleeve) together around the carrier pipe.

Section 3: Design

3.1 Carrier Design

3.1.1 Consideration should be given to adding supplementary carrier pipe wall thickness, pipe depth, or concrete coating in lieu of casing.

3.1.2 The carrier pipe shall be effectively coated, with consideration being given to the application of supplementary coating. See NACE Standard RP0169¹ for details.

3.1.3 The carrier pipe shall be properly supported inside and outside the casing to prevent metallic contact between the casing and the carrier pipe. See NACE Standard RP0286² for details.

3.2 Casing Design

3.2.1 The casing should be kept as short in length as possible. This may lessen the chance of shorting.

3.2.2 For pipelines 20 cm (8.0 in.) in diameter and larger, the diameter of the casing should be a minimum of 10 cm (4.0 in.) larger than that of the carrier pipe. For pipelines smaller than 20 cm (8.0 in.) in diameter, the diameter of the casing is normally a minimum of 5 cm (2 in.) larger than that of the carrier pipe.

3.2.3 Uncoated casing pipe is normally used. The use of coated or nonmetallic casing pipe is not recommended, due to potential shielding problems.

3.2.4 Vent pipes should be installed on both ends of a casing.

3.2.5 The casing vent hole should be at least one-half the diameter of the vent pipe (2.5-cm [1.0-in.] minimum). The casing vent pipe should be a minimum of 5 cm (2 in.) in diameter.

3.2.6 The casing and carrier pipe shall be properly supported for the entire length of the pipe, especially near the ends, to prevent sagging, metallic contact, and to avoid carrier pipe stress. Refer to Paragraphs 4.3 and 4.4.

3.2.7 Properly designed casing end seals shall be installed to prevent ingress of water and debris.

3.2.8 Vent pipes shall be designed, using standard industry methods, to exclude intrusion of water and debris.

3.3 Metallic Isolation

3.3.1 Sufficient electrically nonconductive spacing material shall be specified and installed to prevent metallic contact between the carrier pipe and the

casing, provide adequate support, and minimize coating damage. Refer to Paragraph 4.4.

3.3.2 Electrical testing facilities shall be installed to permit verification of metallic isolation. Refer to Paragraph 4.5.

3.3.3 Metallic short between the casing vent pipe, test leads, and the carrier pipe shall be prevented. Refer to Paragraphs 4.3, 4.4, and 4.5.

3.4 Other Design Considerations

3.4.1 Cathodic protection may be considered in some situations, and applied to the casing as required by conditions and/or regulations. See NACE Standard RP0169 for details.

3.4.2 Consideration may be given to placing inhibited dielectric filler in the annular space. Refer to Appendix A.

3.4.3 Sound engineering practices shall be used in the selection of casing materials.

Section 4: Installation

This section pertains to the installation of new cased pipeline crossings, casing extensions, and new casing installation on existing lines by the split-sleeve method. Installation of a casing at a highway, railway, or other crossing may be required by the permitting agency or owner company.

4.2 The carrier pipe and casing shall be handled and stored in a manner that minimizes coating and end damage. Lifting shall be accomplished utilizing approved slings, wide belts, or appropriate end hooks. If skids are utilized to support the pipe or casing, padding material shall be used to prevent coating damage. In addition, the skids shall be removed upon completion of the installation.

4.3 New Casing Installation

4.3.1 Cased crossings are installed using various techniques including boring, directional drilling, tunneling, and open cutting. If boring or tunneling methods are used, filling of the annular space between the casing and excavation is sometimes required by the permitting agency. Safety is a major factor during all casing installation work, and all applicable government requirements must be followed. If rock or other unexpected obstructions are encountered during boring operations, the use of specialized cutting heads or tunneling with oversized casing and blasting is sometimes necessary.

4.3.2 While fabricating casings, proper butt-weld alignment must be maintained to prevent casing, isolator, or spacer damage during push/pull operations. In addition, slag, bows, etc., must be removed to prevent damage to the carrier pipe, coating, isolator, or spacer. Casing diameter is usually determined by the need to apply concrete coating, epoxy-polymer concrete coating, or isolators to the carrier pipe. Welding of casings should be performed in accordance with the appropriate welding specification. Radiographic inspection of casing welds is normally not required.

4.3.3 If possible, the casing vent pipe should be installed before the carrier pipe to avoid the possibility of coating damage. If the carrier pipe is already in place when the vent hole is cut, extreme care shall be exercised while cutting the vent hole. The use of nonflammable insulating material to protect the pipe coating is often required by the owner company. When two vent pipes are used, the one at the lower elevation should be installed on the bottom of the casing to facilitate possible filling of the casing at a later date. If the vent pipe is "doglegged," adequate separation and nonmetallic support between the vent pipe and carrier pipe is required.

4.3.4 If spiral welding or spiral-weld pipe is used for the casing pipe, internal weld beads should be ground down to allow proper pulling or sliding of the carrier pipe to prevent damage to the isolators and coating.

4.4 Installation of Carrier Pipe

4.4.1 Before the installation of isolating spacers, the carrier pipe coating shall be electrically inspected (i.e., holiday tested or "jeeped") using an approved electrical holiday detector and in accordance with NACE Standard RP0274³ or RP0490.⁴ The casing isolators shall be installed according to the manufacturer's instructions and in the quantity recommended by the manufacturer. The inspector shall ensure that the installation is conducted in a manner that does not damage the carrier pipe coating. Isolator runners (skids) shall be oriented properly. Bolts, if present, should not remain at the bottom (6 o'clock) position. If possible, end caps shall be installed on the carrier pipe to aid in smooth push/pull operations.

4.4.2 Casing isolators shall be carefully selected to ensure they have the mechanical strength required to withstand the actual installation considering all conditions including pipe weight, length of casing, conditions of weld beads, deflections in the casing, and other field conditions. Selection should include an evaluation of the ability of the casing isolators to provide electrical isolation after enduring the rigors of installation. (See NACE Standard RP0286 for additional information.)

4.4.3 The casing shall be visually inspected and, if necessary, cleaned (swabbed) immediately prior to installing the carrier pipe to remove any debris/foreign material.

4.4.4 The carrier pipe shall be installed by a crane or side-boom tractor using slings or belts that do not interfere with the isolators or damage the coating. If attached to the end caps, the pull cable shall be fed through the casing in a manner that does not damage the casing. The alignment of the pipe and casing must be ensured both prior to and during insertion of the carrier pipe into the casing. During the installation operation, it must be ensured that there is no isolator and/or spacer displacement or damage to the carrier pipe coating. The push/pull operation shall continue in a smooth motion until the carrier pipe is properly positioned.

NOTE: Casing isolating spacers may slide along the carrier pipe during installation if not installed properly, if the casing is bent, or if the installation is out of line. Inadequate support of the pipe allows the pipe to sag and make metallic contact with the

casing. The inspector should be aware of this potential problem during the installation.

4.4.5 The cased crossing shall be tested in accordance with Section 5 to confirm that the casing and carrier pipe are not electrically shorted. The carrier pipe and casing shall be cleaned as necessary for the installation of the end seals in accordance with design specifications and the manufacturer's recommendations. All coating damage shall be repaired in accordance with the coating vendor's or applicable specifications.

4.4.6 The previous sections on handling pipe are also applicable to the installation of uncoated carrier pipe.

4.5 Test Leads: Test lead wires shall be installed on the carrier pipe using a thermite weld or other approved process. Test lead wires are required on the carrier pipe at both ends of the casing. In the event that the original cable is lost or damaged, a spare lead wire may be installed to perform the tests in Appendix B and to confirm the integrity of the other lead. The test lead-to-pipe connection shall be properly coated and any damage to the pipe or pipe coating shall be repaired in accordance with applicable specifications. Wrapping the test leads around the vent pipe shall be avoided to prevent the possibility of electrical shorting. Test lead wires are required for the casing if nonmetallic vent pipes are installed or if the metallic vent pipes use mechanical couplings/fittings. The use of color-coded test lead wires is desirable.

4.6 Backfilling: The casing and carrier pipe shall be backfilled with debris-free material. The carrier pipe and casing shall be supported using earth-filled bags, compacted earth, or other methods to prevent settlement during the backfilling operation. Caution must be exercised to prevent test-lead damage, which is a common cause of shorting. Testing as described in Section 5 shall be performed upon completion of the backfilling operation.

4.7 Split-Casing Extensions and Installations

4.7.1 Extension of existing casings or construction of new casings on existing pipelines often involves installation by the split-casing/split-sleeve method. This method is required if the pipeline cannot be taken out of service and the subsequent blow-down (gas), or drain-up (liquid), and cutting out of the road crossing to allow a casing to be slipped over the pipeline is not feasible or cost-effective.

4.7.2 Split-casing extensions are normally specified to match the size of the existing casing. Occasionally the configuration of the existing pipeline requires the installation of an oversized casing extension. In this case, a standard-welded or conical reducer may be used to achieve the size transition.

4.7.3 The carrier pipe section to be cased shall be carefully excavated. The carrier pipe shall be cleaned, properly coated where necessary, and properly supported to prevent possible damage due to sagging. After existing casing seals and vents are removed, the vent-pipe hole shall be capped with a steel plate. To prevent coating damage, the carrier pipe shall be protected during burning and welding operations with an insulating shield of nonflammable material.

4.7.4 The existing casing ends shall be prepared for welding in accordance with applicable specifications. The carrier pipe coating shall be inspected and repaired. The electrical-isolating and spacing materials shall be installed in accordance with applicable specifications.

4.7.5 The pipe to be used in the casing extension shall be specified to provide metallurgical and physical compatibility with the existing casing.

If a manufactured split casing is not used, splitting of the casing shall be performed in a manner that minimizes warping or disfigurement of the pipe. Hinges are sometimes welded to the casing to maintain proper alignment of the casing halves during installation. The new casing vent hole shall be cut using the procedure described in Paragraph 4.3.3.

4.7.6 The split casing shall be carefully positioned over the existing carrier pipe in a manner that avoids any damage to the pipe, coating, or spacing materials. Seam welding shall be performed in accordance with applicable specifications. The casing seams are often tack welded at specified intervals prior to the continuous welding operation to prevent warping. During this welding operation, nonflammable, insulating backing material shall be used to protect seam areas on the carrier pipe while the split casing halves are being properly supported. The installation of new vent piping, test leads, and backfilling shall be performed in accordance with Paragraphs 4.3.3, 4.5, and 4.6, respectively.

Section 5: Maintenance And Repair

5.1 Actions necessary in the course of pipeline maintenance may include:

- Eliminating metallic contact
- Removing the casing
- Replacing the carrier pipe
- Providing supplemental cathodic protection to the casing
- Filling the casing with a dielectric material
- Installing a new crossing
- Monitoring the condition of the casing
- Coating or recoating the carrier pipe
- Replacing end seals
- Removing electrolyte from inside the casing

5.2 Maintenance of cased crossings is sometimes necessary. Typical situations include:

- Corrosion or other damage to the carrier pipe or casing pipe is indicated by inspection.
- Casing extension or removal is necessary.
- The casing is in electrical metallic contact with (shorted to) the carrier pipe.
- The casing becomes filled or partially filled with electrolyte and an internal "electrolytic" contact develops.

5.2.1 The casing could have come into electrical contact with the carrier pipe in several ways:

- The carrier pipe moved in the casing, causing it to come into metallic contact with the casing at some point; such contact often occurs at the ends of the casing.
- Spacing materials failed during or after the original installation of the pipeline.
- The pipe was inadequately supported within the casing, allowing it to sag and come into metallic contact with the bottom of the casing.
- The carrier pipe was intentionally shorted or installed without isolators.
- A foreign object such as a shovel or other metallic material present at the construction site was accidentally left in the casing.
- A short developed between the test lead and the vent pipe or the casing test leads.

5.3 Maintenance of Vents and Test Leads: Maintenance of casing vents includes coating at the soil/atmosphere interface and painting, repair, or replacement of vents and vent caps. Test leads shall be checked annually to determine their integrity.

5.4 Clearing of Shorted Casings: The point of metallic contact between the carrier pipe and the casing (such as contact with the metallic portions of end seals, isolating spacers, bond wires or straps, test leads, debris, or the casing itself) can often be removed. Established construction techniques shall be used to realign the pipe or casing to eliminate pipe metallic contact. Equipment used in this situation includes hydraulic jacks, tripods, air bags, side-boom slings, and belts. The pipe and casing shall be maintained in this realigned position by the use of supports such as compacted earth, sandbags, or concrete piers placed under the pipe. In certain situations, the elimination of a metallic contact may be accomplished by removing a portion of the casing.

Once metallic contact is eliminated, spacing materials, end seals, vents, and test leads shall be reinstalled.

CAUTION: Engineering, metallurgical, and operational concerns and regulatory requirements shall be considered before moving the carrier pipe.

5.5 Filling of Casings: In certain situations, casings may be filled with dielectric material or corrosion inhibitors in an attempt to eliminate a corrosive environment. Casing-filling procedures are provided in Appendix A.

Section 6: Monitoring

6.1 If a casing is suspected of compromising the integrity of the pipeline, the following methods may be used to determine whether the casing is shorted to the carrier pipe:

6.1.1 A recommended initial test for a shorted casing is to compare the casing-to-electrolyte potential with the pipe-to-electrolyte potential. A shorted casing may exist if there is a small differential or if there is no differential between the pipe-to-electrolyte potential and casing-to-electrolyte potential. If a test suggests that the casing may be shorted, subsequent testing should be performed.

NOTE: If cathodic protection is applied to the casing, the cathodic protection system normally must be disconnected from the casing and allowed to depolarize before any tests are conducted. The presence of direct-connected galvanic anodes on the casing during the test may negate the test results.

6.2 Monitoring: One or more of the following basic electrical test methods should be used to monitor pipelines and casings on an annual basis. Procedures are provided in Appendix B.

6.2.1 Potential Survey: This method is the initial test conducted to identify a shorted casing. A voltmeter and a reference electrode are used to conduct the test.

6.2.2 Internal Resistance: This method indicates whether direct metal-to-metal contact exists between a carrier pipe and the casing pipe by measuring electrical resistance. The value is obtained using standard corrosion field instrumentation. A battery and a combination volt-ammeter or four-pin soil resistance meter along with four test leads (two on casing, two on carrier pipe) are used to conduct the test.

This is an especially useful test immediately after construction and before the carrier pipe is tied in. If this test is performed after the carrier pipe is tied in, the resistance of the parallel path through the soil must be considered. A low resistance value indicates a short, and that the pipe should be removed or the short cleared.

6.2.3 Four-Wire IR Drop: This method may indicate the existence and location of a short. A battery, suitable test leads or probe bars, and a combination volt-ammeter are used to conduct the test. A four-pin resistance meter or megger to determine the as-found resistance between the carrier and casing may also be used as part of this test.

6.2.4 Cycling Rectifier: Cycling the cathodic protection rectifier is a method used to evaluate the electrical isolation between pipe and casing. For this test, the nearest influencing rectifier(s) is interrupted. An interrupter, voltmeter, and reference electrode are used to conduct the test. If the pipe-to-electrolyte potentials taken on the pipe and the casing are identical during both the rectifier "on" and "off" cycles (with the reference electrode at the same position), a shorted casing is indicated.

6.2.5 Casing Depolarization: This technique verifies isolation status by discharging a direct current (DC) from the casing. A significant potential difference occurs between the casing and carrier pipe if the two structures are not in metallic contact. A temporary cathode or ground electrode, variable DC power source, and combination voltammeter are used to conduct the test.

6.2.6 Direct Resistance Measurement: This technique uses a four-pin resistance meter or megger to determine the as-found resistance between the carrier and casing.

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This method works best with the four-wire method. Using fewer than four wires introduces a lead-resistance problem into the circuit.

6.2.7 Pipe/Cable Locator: The presence and location of a pipe-to-casing metallic contact may also be approximated by following a low-power audio or radio signal (pipe locator trace) set between the pipe and the casing. The signal returns at the point of metallic contact, which should be verified from the opposite end.

6.3 Instrumented ("Smart") Pigs

6.3.1 If feasible and practical, in-line inspection of a pipeline may be used to determine the presence or absence of pitting-corrosion damage on carrier pipe inside a casing. In-line inspection techniques are capable of detecting many types of corrosion damage with a high degree of accuracy. However, they may not detect metal-to-metal contact between the casing and carrier pipe.

6.4 Leakage Survey

6.4.1 Visual Inspection: The casing vent and the area in the vicinity of the casing end may be observed for evidence of product leakage such as product, product odor, or dead and dying vegetation.

6.4.2 Instrumented Surveys for Pipe Carrying Combustible Hydrocarbons: Appropriate leak-detection instruments, such as combustible gas indicators, may be used to analyze the atmosphere within a casing for the presence of combustible hydrocarbons. Pressure tests or other leak-detection devices are used on other systems. These surveys should be done at the frequency required by the applicable code or in accordance with the operating company's practice.

References

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2. NACE Standard RP0286 (latest revision), "The Electrical Isolation of Cathodically Protected Pipelines" (Houston, TX: NACE).
3. NACE Standard RP0274 (latest revision), "High-Voltage Electrical Inspection of Pipeline Coatings Prior to Installation" (Houston, TX: NACE).
4. NACE Standard RP0490 (latest revision), "Holiday Detection of Fusion-Bonded Epoxy External Pipeline Coatings of 250 to 760 μm (10 to 30 mils)" (Houston, TX: NACE).
5. ASTM D 938 (latest revision), "Standard Test Method for Congealing Point of Petroleum Waxes, Including Petrolatum" (West Conshohocken, PA: American Society for Testing and Materials [ASTM]⁽¹⁾).
6. ASTM D 937 (latest revision), "Standard Test Method for Cone Penetration of Petrolatum" (West Conshohocken, PA: ASTM).

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- Peabody, A.W. *Control of Pipeline Corrosion*. Houston, TX: NACE, 1967.

⁽¹⁾ ASTM, 100 Barr Harbor Drive, West Conshohocken, PA 19428.

⁽²⁾ American Gas Association (AGA), 1515 Wilson Blvd., Arlington, VA 22209.

Appendix A: Typical Casing-Filling Procedures

Preparation

Casing Vent Pipes

A vent pipe shall be installed on each end of the casing, and an opening in the casing at the vent-pipe connection shall be provided. The opening shall be adequate in size to allow for the flow of casing filler into the casing (a minimum vent pipe opening of 5 cm [2 in.] is recommended). Greater flexibility in the fill operation is provided by installing a bottom-vent pipe on the lower elevation of the casing and a top-vent pipe at the higher elevation. The vent pipes and the casing annulus must be free of restrictions to allow adequate flow of the casing-filler material.

Casing End Seals

Casing end seals shall be inspected to ensure their integrity and ability to contain the casing-filler material during installation. If necessary, new casing end seals shall be installed prior to the filling operation.

Fill Procedure

Filler Material

Casing-filler material is composed mainly of petrolatum wax or petroleum-based compounds and contains corrosion inhibitors, plasticizers, and thermal extenders. The following are recommended characteristics for filler material:

- A minimum congeal point of 41°C (105°F), in accordance with ASTM D 938⁵
- A 50 minimum cone penetration, in accordance with ASTM D 937⁶
- Is nonhazardous and nonflammable
- Is not water-soluble

A heated, insulated tanker with a permanent, variable-flow pump should be used to fill the casing. For drum installation, a 10:1 ratio mastic pump with inductor plate is required.

An environmentally acceptable corrosion inhibitor may be poured down the fill-vent pipe just prior to the installation of the casing filler.

Hoses shall be connected to the fill-vent pipe. The filler material shall be pumped into the casing until it is full. If the casing contains water, the casing filler shall be installed through the vent pipe at the high elevation of the casing.

Vapor Phase Inhibitor

A vapor phase inhibitor may be injected into the casing annulus through the vent pipes. The inhibitor is allowed to vaporize and coat the carrier pipe. Periodically the inhibitor must be replenished.

Analysis of Casing Filler Material

Upon completion of the filling procedure, casing-fill percentage should be calculated using Equation (A1).

$$\frac{\text{Actual Volume}}{\text{Theoretical Volume}} \times 100 = \text{Casing Fill Percentage} \quad (\text{A1})$$

This calculation gives a rough approximation of the effectiveness of the casing filling. Individual casing-fill percentages may vary considerably.

Casing-fill percentages may be unusually low because of:

- A casing length that is smaller than that depicted on the as-built drawings
- Variations in the thickness of the coating on the carrier pipe
- Accumulation of dirt, mud, etc., in the casing
- Water entrapped in the casing during the fill
- Failure to take into account the displacement of the isolators

Casing-fill percentages of individual casings may be unusually high because of:

- Discrepancies on the as-built drawings
- Holes in the casing
- Leaks in the casing end seals

Taking the average of several individual casing-fill percentages provides a useful measure of the overall performance of the casing-filling procedure. An average casing-fill percentage lower than 85% is considered questionable and should be investigated.

Appendix B: Monitoring Techniques

1. Potential Survey

Purpose

Potential surveys of pipelines and casings are made to monitor cathodic protection and are the initial tests conducted to identify shorted casings. The presence of a metallic contact may also be evaluated by measuring the pipe-to-electrolyte and casing-to-electrolyte potentials under the conditions shown below and comparing these values to a known shorted condition established at the opposite end of the casing (using test leads and vent pipes).

Procedure

Potential measurements (surveys) of pipelines and casings are made using a voltmeter and a reference electrode (usually a copper-copper sulfate electrode [CSE]).

More definitive results are obtained if the cathodic protection current source is cycled on/off while the pipe and casing potentials are recorded.

1. Measuring pipeline potential: One lead of the voltmeter shall be connected to the pipeline by way of the test lead or probe bar. The other lead of the voltmeter shall be connected to the reference electrode, which is placed on the ground directly over the pipeline and near the end of the casing (see Figure B1).

2. Measuring casing potential: One lead of the voltmeter shall be connected to the casing by way of the vent, test lead, or probe bar. The other lead of the voltmeter shall be connected to the reference electrode, which shall be placed at the same location as where the pipeline potential was taken (see Figure B1).

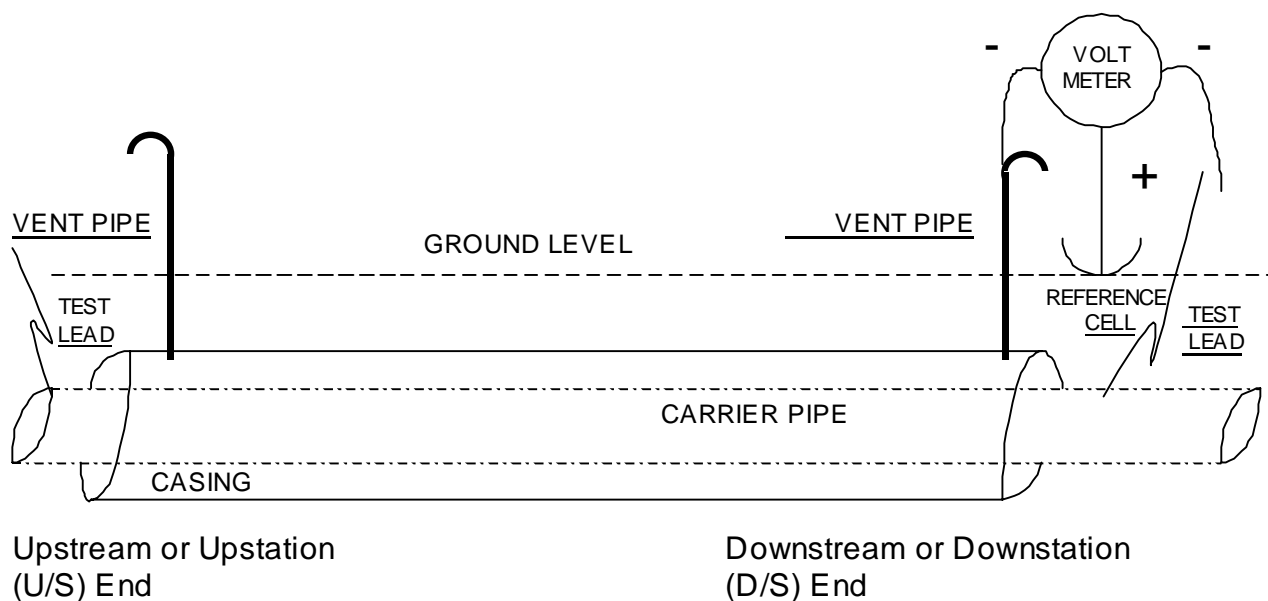


FIGURE B1: Potential Survey Measurement

Note: The electrode shall be placed near the end of the casing directly over the carrier pipe. The reference electrode shall not be placed directly over the casing. The location of the end of the casing can usually be verified with a conductive pipe locator.

Analysis

A "clear" or not shorted casing is indicated by a potential difference between the casing and the carrier pipe. For example, a pipe-to-soil potential of 1.6 V CSE and a casing potential of 0.65 V CSE has a potential difference of 0.95 volts and would indicate the casing is clear.

A shorted casing may exist if a small potential difference exists between the pipeline potential and the casing potential. This is typically less than 100 mV. Additional testing should be conducted if the difference in potential is 100 mV or less.

If operator data and experience indicate that it is appropriate, a difference in potential as small as 20 mV, or as large as 200 mV, may be considered a criterion indicating that the casing under test requires further examination.

2. Internal Resistance Test

Purpose

This technique may indicate whether direct metal-to-metal contact exists between a carrier pipe and a casing pipe by measuring electrical resistance.

Only qualified cathodic protection personnel should analyze the results when this test is run on a buried/tied-in pipeline.

Procedure

This procedure requires an appropriate wet-cell battery (e.g., car battery), a properly rated ammeter or shunt, a properly rated resistor, sufficient lead wire, clamps, and a multimeter. See cautionary note following Figure B2.

1. The pipe-to-casing potential shall be measured at terminals T1 and T2. See Figure B2.
2. One battery lead shall be attached to a casing test lead at T3 (if no test lead is available then the casing vent [T1] may be used). The other lead shall be connected in series with the ammeter to the carrier pipe at T4.
3. A constant current shall be applied between terminals T3 and T4. The current (I) shall be measured in amperes.
4. The pipe-to-casing potential shall be measured between terminals T1 and T2 with the current applied.

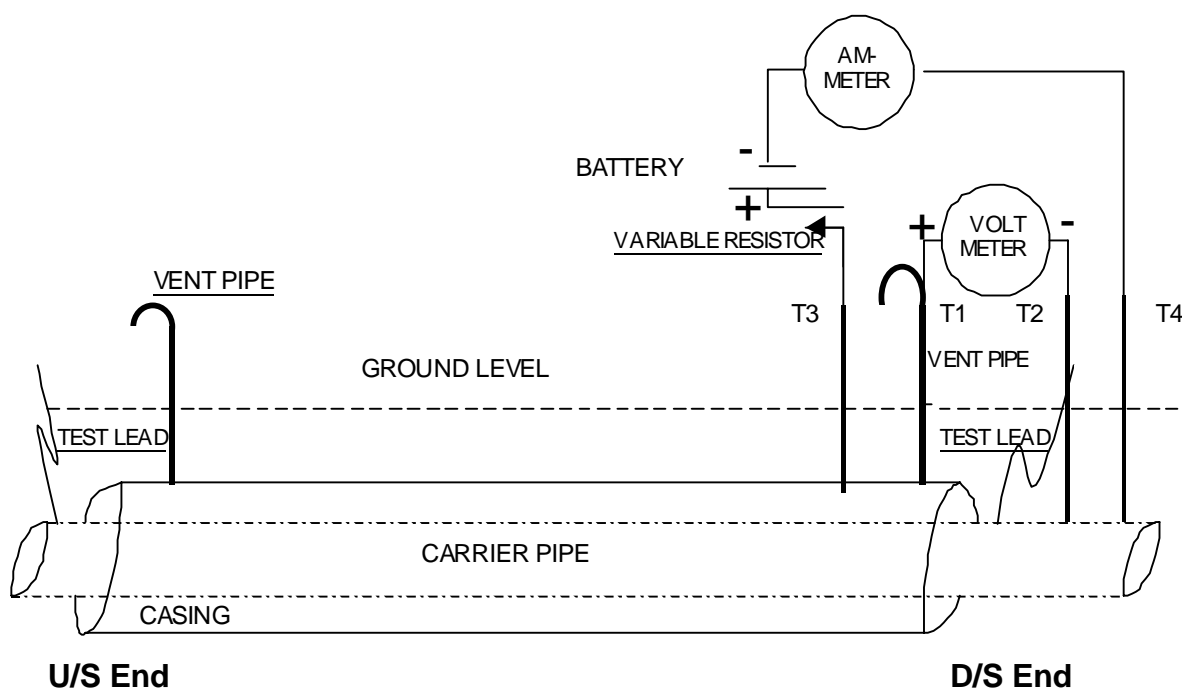


FIGURE B2: Internal Resistance Test

CAUTION: It is very dangerous to short the leads of a wet-cell battery together. The above procedure may produce a direct short if a metal-to-metal contact exists between the carrier pipe and the casing. Therefore, only dry-cell batteries or a wet-cell battery with a properly rated resistor installed in series shall be used. Maximum battery output shall be limited to 10 A.

Note: A four-pin soil resistivity meter may replace the battery, voltmeter, and ammeter shown in Figure B2 so that the resistance may be read directly. If a four-pin soil resistivity meter is used, the locations of the test leads are the same as those shown in Figure B2. C1 is connected to T3, P1 to T1, P2 to T2, and C2 to T4.

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Analysis – Resistance Calculation using Ohm's Law

The pipe-to-casing potential difference (ΔV) is calculated by subtracting the result of Step 4 from the result of Step 1. Because Ohm's Law states that the direct current

flowing in an electric circuit is directly proportional to the voltage applied to the circuit, ΔV shall be divided by the current (I). A casing-to-pipe (metal-to-metal) contact may exist if the resultant value is less than 0.01 ohm.

Example 1

A potential survey indicates that the difference between the casing potential and the pipeline potential is less than 100 mV. Using the above procedure to perform an internal resistance test, a potential of 0.090 V is measured on terminals T1 and T2 prior to the application of current. After a current of 1.70 A is applied on terminals T3 and T4, a pipe-to-casing potential of 0.106 V is measured.

Pipe-to-Casing Potential Before Current is Applied:	0.090 V
Pipe-to-Casing Potential with the Current Applied:	<u>-0.106 V</u>
Change in Potential (ΔV):	<u>-0.016 V</u>

By dividing ΔV by current (I), as in Equation (B1), the value of the resistance (R) is obtained:

$$0.016 \text{ V} \div 1.7 \text{ A} = 0.0094 \text{ } \Omega \quad (\text{B1})$$

The resistance is 0.0094 Ω . Because the pipe-to-casing resistance is less than 0.01 Ω , the presence of a short is indicated.

Note: Because the pipe to casing resistance is so low considering the circuit resistance, the presence of an electrical short is indicated.

Example 2

A pipe-to-casing potential of 0.100 V is measured between terminals T1 and T2. After 1.70 A of current is applied between terminals T3 and T4, a pipe-to-casing potential of 0.302 V is measured between terminals T1 and T2.

Pipe-to-Casing Potential Before Current is Applied:	0.100 V
Pipe-to-Casing Potential After Current is Applied:	<u>-0.302 V</u>
Change in Potential (ΔV):	<u>-0.202 V</u>

By dividing ΔV by current (I), as in Equation (B2), the value of the resistance (R) is obtained:

$$0.202 \text{ V} \div 1.7 \text{ A} = 0.12 \text{ } \Omega \quad (\text{B2})$$

The resistance is 0.12 Ω . Because the pipe-to-casing resistance is greater than 0.01 Ω , pipe-to-casing (metal-to-metal) contact is not indicated.

Note: Because the pipe to casing resistance is still quite low considering the circuit resistance, the presence of an electrical short is not indicated; however, additional testing may be necessary to confirm the casing condition.

3. Four-Wire IR Drop Test for Cased Crossings

Purpose

This method may indicate the presence and location of a metallic short to the casing.

Procedure

1. Measuring the Linear Resistance of the Casing

(a) The potential difference shall be measured between terminals T3 and T4 while a measured battery current is simultaneously passed between terminals T1 and T2 (see Figure B3). This can be done with suitable test points (vents or test leads), or the use of probe bars.

(b) The battery current in amperes is divided by the change in potential difference from T3 to T4 (ΔV) in mV to express the calibration factor in A/mV, as shown in Equation (B3).

$$\text{Calibration Factor 1} = \frac{\text{Battery Current}}{\text{Potential Difference from T3 to T4 } (\Delta V)} \quad (\text{B3})$$

(c) Calibration Factor 2 is determined by dividing the Factor obtained from Table B1 by the length of the pipe, as in Equation (B4). The corresponding value in the Factor column is found for the given wall thickness and diameter of the pipe.

$$\text{Calibration Factor 2} = \frac{\text{Factor (from Table B3)}}{\text{Length T3 to T4}} \quad (\text{B4})$$

(d) If the value for Calibration Factor 1 is within $\pm 5\%$ of Calibration Factor 2, the tester shall proceed to Step 2. If Calibration Factor 1 is not within $\pm 5\%$ of Calibration Factor 2, the test shall be repeated until factors are within 5%.

Note: Equation (B5) can be used to convert ohms to amperes/mV (resistance to conductance):

$$A/mV/m = \frac{I}{\mu \Omega/m} \times 1,000 \quad (\text{B5})$$

2. Establishing the Circuit (Upstream [U/S] End)

(a) The circuit shall be established by connecting the negative terminal of the battery to T2 (pipe lead), and connecting T1 (upstream vent) to the positive terminal of the battery. (See Figure B4).

(b) The inside terminals T3 and T4 are the same as those used for the measurement of potential

difference in Figure B3. The voltage drop is measured across the current-measuring span (between T3 and T4) while a known amount of battery current passes between T1 and T2.

(c) The percent of the distance "a" to the contact from the upstream end (T4) is calculated using Equation (B6).

$$\text{Distance (in percent) from T4} = \frac{\Delta V (T4) \times \text{Calibration Factor}}{\text{Current}} \times 100\% \quad (\text{B6})$$

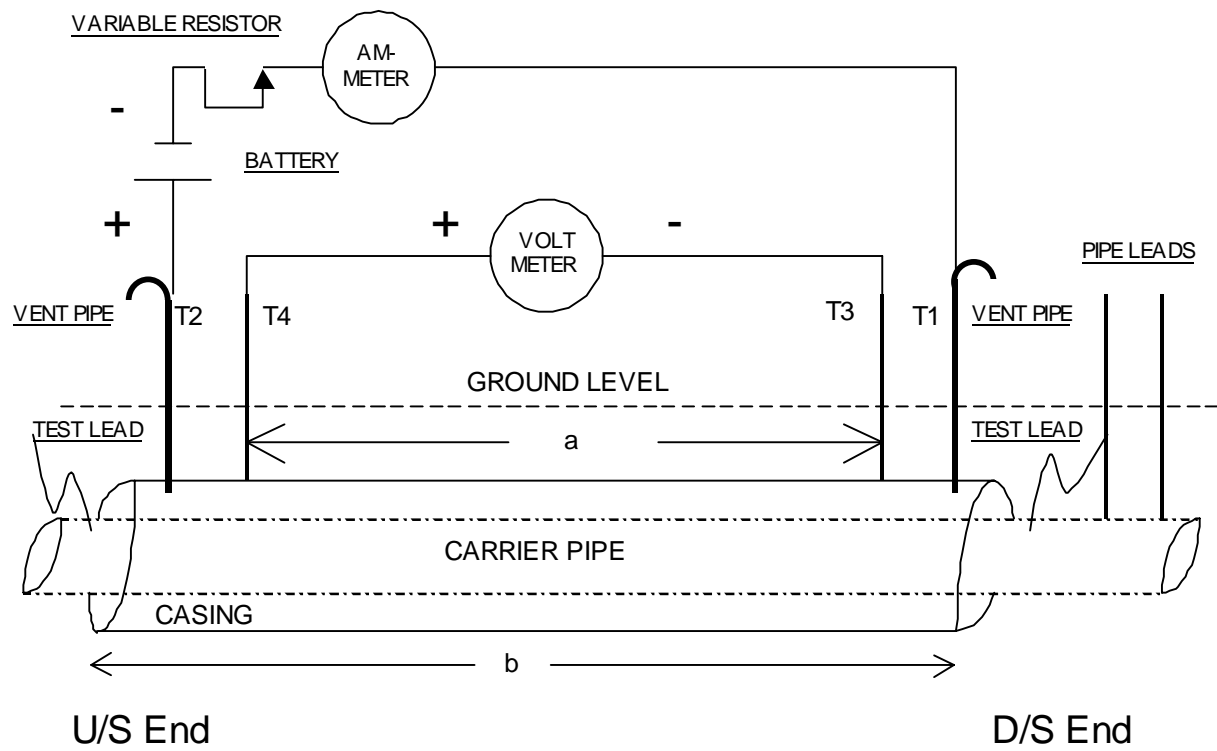


FIGURE B3: Four-Wire IR Drop Test (Calibrating the Inside Terminals)

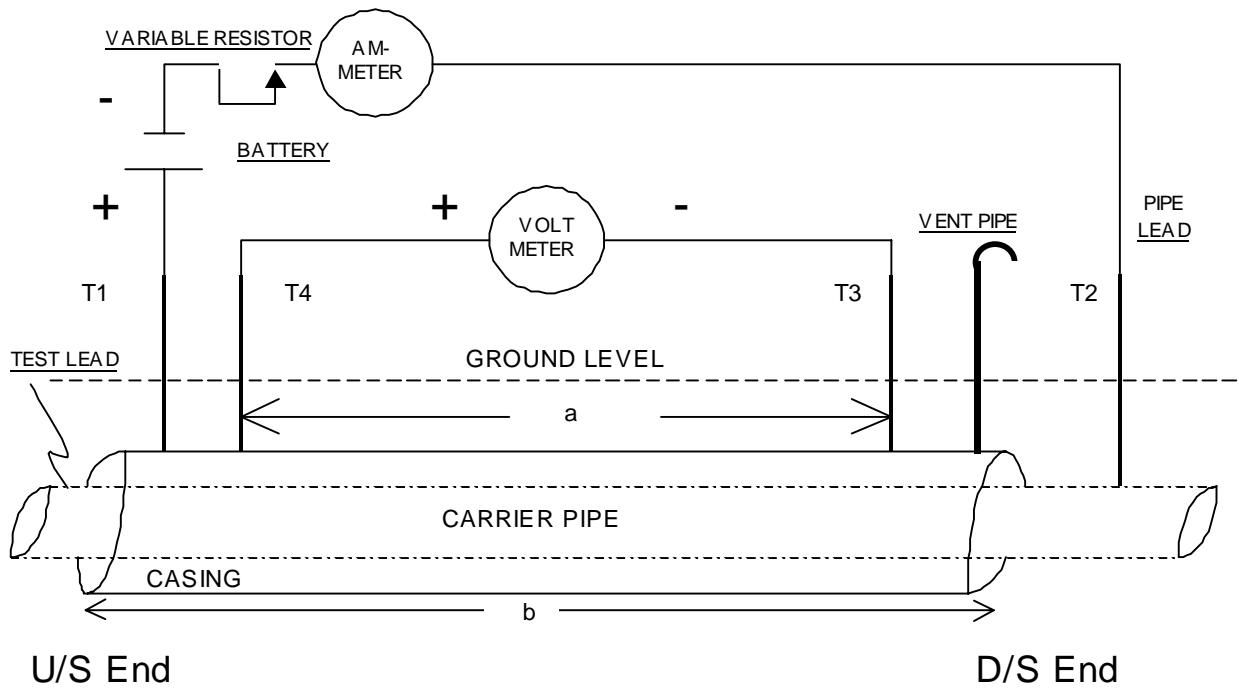


FIGURE B4: Establishing a Circuit for a Four-Wire IR Drop Test (U/S End)

3. Establishing the Circuit (Downstream [D/S] End)

- (a) The circuit shall be established by connecting the battery negative to T2 (pipe lead).
- (b) T1 (downstream vent) shall be connected to the positive side of the battery as shown in Figure B5.

(c) T3 and T4 shall remain the same for measurement of potential difference as shown in Figure B3.

(d) The percentage of distance "a" from T3 shall be calculated as in Equation (B7).

$$\text{Distance (in percent) from T3} = \frac{\Delta V (T3) \times \text{Calibration Factor}}{\text{Current}} \times 100\% \quad (\text{B7})$$

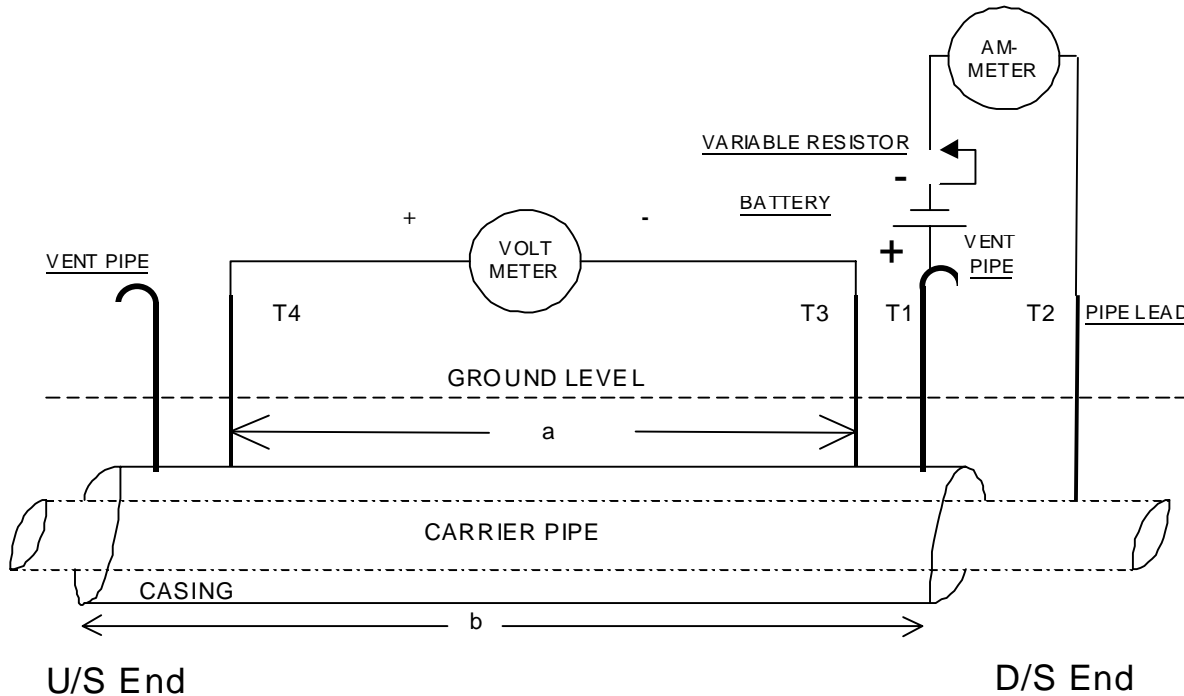


FIGURE B5: Four-Wire IR Drop Test (Establishing the Circuit) (D/S End)

CAUTION:

- Proper placement of the insulated probe bar and test leads is required to obtain contact for measurement of the IR drop on T3 and T4, or erroneous readings may result.
- If more than one metal-to-metal contact exists, this test may not accurately identify the location of the shorts.
- All safety precautions shall be implemented when lead acid batteries are used.

Example 1

A pipe casing is 76.2 cm (30.0 in.) in diameter, 12.2 m (40.0 ft) long, and has a wall thickness of 7.92-mm (0.312-in.).

Casing Data: Length a = 12.2 m (40.0 ft)
Length b = 15 m (49 ft)
Diameter = 76.2 cm (30.0 in.)
Wall Thickness = 7.92 mm (0.312 in.)

Step 1: Find the calibration factor.

A potential difference of 0.465 mV is measured between T3 and T4 before the application of current at T1 and T2. A potential difference of 1.50 mV is measured after the application of current (9.00 A).

Potential Difference Before Current is Applied:	0.465 mV
Potential Difference After Current is Applied:	-1.500 mV
Change in Potential (ΔV):	<u>-1.035 mV</u>

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The calibration factor is calculated using a modified version of Equation (B3):

$$\text{Calibration Factor} = \frac{9.00 \text{ A}}{1.035 \text{ mV}} = 8.70 \text{ A/mV} \quad (\text{B3})$$

Note: This calibration method is similar to that used to calibrate a typical shunt used in a rectifier.

Check Step 1 using Table B1:

- Find the Factor for a pipe with a 76.2-cm diameter and 7.92-cm wall thickness in the table.
- Divide the Factor by the length to find the Calibration Factor. The equation is a modified version of Equation (B4):

$$\text{Calibration Factor} = \frac{105.41 \text{ A/mV/m}}{12.2 \text{ m}} = 8.64 \text{ A/mV} \quad (\text{B4})$$

Because these two calculations are within $\pm 5\%$, proceed to Step 2.

Step 2: Measure the voltage with current applied at the upstream end.

Calculate the distance (in percent) from contact to T4 using a modified version of Equation (B6):

$$\text{Distance (in percent) to contact from T4} = \frac{1.035 \text{ mV} \times 8.70 \text{ A/mV} \times 100\%}{9.00 \text{ A}} = 100\% \quad (\text{B6})$$

Check Step 2 Using Table B1:

- Find the resistance for a pipe with a 76.2-cm diameter and 7.92-cm wall thickness in Table B1.
- Determine the length from the positive, inside terminal to the short. The resulting equation is a modified version of Equation (B5):

$$\begin{aligned} \text{Length} &= \frac{1.035 \text{ mV} \times 10^{-3}}{9.00 \text{ A} \times 9.48 \times 10^{-6} \text{ ohms/m}} \\ \text{Length} &= 12.1 \text{ m} \end{aligned} \quad (\text{B5})$$

Because the length from the positive, inside terminal to the short is equal to the entire length of the pipe, this test indicates that the short is at the downstream end.

Step 3: Measure the voltage with current applied at the downstream end.

Calculate the distance (in percent) to contact from T3 using a modified version of Equation (B7):

$$\text{Distance (in percent) to contact from T3} = \frac{0 \text{ mV} \times 8.70 \text{ A/mV} \times 100\%}{9.00 \text{ A}} = 0\% \quad (\text{B7})$$

A potential change due to the presence of current is not observed between T3 and T4, confirming that the metal-to-metal contact is located at the downstream end of the casing.

Notes:

If a short is located near the middle of the casing and all of the currents are confirmed by the IR drop method, the location of the short may be determined by finding the percentage of current at either end of the pipe and then calculating the distance in A/m (A/ft) (as shown in Step 2).

If the currents do not sum algebraically, the results of the testing shall be considered inconclusive.

Alternate Method: Lineal Conductance Values for the Casing

The preceding calibration procedure can also be used to provide the *actual lineal resistance* for the casing (voltage drop between casing test leads, divided by applied current). Then using Equation (B8), the distance from the end of the casing to the point of contact can be calculated:

$$L_{C1} = \frac{R_{C1}}{R_{CT}} L_{CT} \quad (B8)$$

Where:

- L_{C1} = Distance from end of casing to point of contact
- R_{C1} = Lineal casing resistance from end of casing to point of contact
= $\Delta V_1 / I$
- R_{CT} = Total lineal resistance of casing
- L_{CT} = Total length of casing

The actual lineal resistance for the casing should be compared with the *theoretical lineal resistance* for the casing, found in Table B1.

When the test is repeated at the opposite end of the casing (End No. 2), Equation (B9) can be used to find the distance from that end of the casing to the point of contact

$$L_{C2} = \frac{R_{C2}}{R_{CT}} L_{CT} \quad (B9)$$

For the test results to be accurate, $R_{C1} + R_{C2} = R_{CT}$ and $L_{C1} + L_{C2} = L_{CT}$. The ends of the casing are considered to be the locations where the test leads for the potential measurements are located. The potential measured across the casing is the potential change that occurs when current is applied.

4. Cycling the Rectifier

Purpose

Measurement of structure-to-earth potentials under steady-state conditions of applied cathodic protection may not provide conclusive evidence regarding the state of electrical isolation between casing and pipeline. The same potential measurement, if taken while the cathodic protection rectifier is being cycled, may provide additional information for evaluation of casing isolation conditions.

Procedure

This technique may be applied to a pipeline survey using an interrupter in the most influential cathodic protection rectifier unit. The location of the cycling rectifier selected shall be sufficiently remote from the casing under test so that anodebed voltage gradients do not influence the measurement.

1. Pipeline and casing potentials shall be measured with the cathodic protection current applied.
2. Step 1 shall be repeated at the same instant that the cathodic protection current is switched off.

Analysis

If the ON and OFF potentials from the casing are close in magnitude to the ON and OFF potentials of the carrier pipe, the presence of an electrical (metallic) short may be indicated.

Note: If water or soil is present in the casing, this test procedure does not give a conclusive result. In such situations, additional testing techniques should be employed.

5. Casing Depolarization Test

Purpose

Isolation may be verified by discharging DC from the casing. If the two structures are not metallurgically connected, a significant potential difference occurs between the casing and carrier pipe.

Procedure

1. A temporary metallic structure shall be constructed laterally to, and spaced an appropriate distance from, the carrier and casing (a spacing of 15 m [50 ft] is usually an adequate distance). Steel rods driven into the earth or sheets of aluminum foil in contact with the earth (usually placed in standing water) may provide an adequate temporary structure.

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2. The negative terminal of a variable DC power source shall be connected to the temporary metallic structure.
3. The positive terminal of the same variable DC power source shall be connected to the casing.
4. A reference electrode shall be positioned over the carrier pipe near the casing end.
5. An appropriate DC voltmeter shall be used to measure and record the carrier and casing potentials.
6. A small increment of current (0.1 A is a satisfactory first increment of current) shall be discharged from the casing for a short period of time, such as one or two minutes.
7. The current shall be interrupted; then the carrier and casing instant-off potentials shall be measured and recorded to determine the effect of the applied current; the increment of current shall also be recorded.
8. Steps 6 and 7 shall be repeated using additional increments of current (e.g., 0.2, 0.3 A). A minimum of three different values of test current and measurement of the effects should be taken. The amount of current required for an effective evaluation varies due to the size of the structure and condition of any coating present. A maximum of 10 A of DC should adequately develop significant potential shifts.

Analysis

A. Casing Shorted

If the casing is shorted, the casing-to-soil potential shifts in a positive direction. The pipe-to-soil potential also shifts in a positive direction, usually by about the same magnitude as the casing. As subsequent steps are taken, the pipe-to-soil potential largely tracks the positively shifting potentials of the casing.

B. Casing Clear

If there is no short, the pipe-to-soil potential may shift in a positive direction by only a few millivolts, whereas there will be a dramatic shift in the casing-to-soil potential. In some cases, the pipe-to-soil potential may shift in a negative direction by a few millivolts.

If the casing potential shifts in a positive direction and the carrier (pipeline) potential remains near normal, electrical isolation is indicated. If the casing and pipeline potentials both shift in the positive direction, a shorted condition is indicated. Examples B1 and B2 illustrate values that indicate electrical isolation (casing clear), and Example B3 illustrates values that indicate an electrically shorted condition (casing short).

EXAMPLE B1

				P/S Pot.	C/S Pot.	Potential Diff.
Initial Readings				0.975	0.850	0.125
Step 1	6.0	Volts	0.25 Amps	0.974	0.710	0.264
Step 2	18	Volts	0.68 Amps	0.975	0.505	0.470
Step 3	45	Volts	1.0 Amps	0.981	0.210	0.771
Step 4	65	Volts	1.8 Amps	0.986	+0.0100	0.996

Conclusion: Casing is clear (not shorted).

EXAMPLE B2

				P/S Pot.	C/S Pot.	Potential Diff.
Initial Readings				1.250	1.21	0.04000
Step 1	6.0	Volts	0.0860 Amps	1.139	0.700	0.4390
Step 2	18	Volts	0.258 Amps	1.104	0.140	0.9640
Step 3	30	Volts	0.413 Amps	1.060	+0.240	1.300
Step 4	42	Volts	0.566 Amps	1.022	+0.490	1.512

Conclusion: Casing is clear (not shorted).

EXAMPLE B3

					P/S Pot.	C/S Pot.	Potential Diff.
Initial Readings					1.246	1.242	0.0040
Step 1	6.0	Volts	0.234	Amps	1.211	1.195	0.016
Step 2	18	Volts	0.594	Amps	1.050	0.9800	0.070
Step 3	30	Volts	1.00	Amps	0.7960	0.7100	0.086
Step 4	45	Volts	1.20	Amps	0.6100	0.5400	0.070
Step 5	75	Volts	2.00	Amps	0.1350	0.1000	0.035

Conclusion: Casing is shorted.

NOTE: During this test, current is being discharged from the casing and this could result in creating an interference condition with other structures.

6. Use of Pipe/Cable Locator

The presence and location of a pipe-to-casing metallic contact may also be approximated by following a low-power audio or radio signal (pipe locator trace) set between the pipe and the casing. The signal returns at the point of contact, which should be verified from the opposite end.

Table B1: Pipe Data

OD		Wall Thickness		Weight		Resistance		Factor		External Area			
cm	in.	mm	in.	kg/m	lb/ft	μohm/m	μohm/ft	A/mV/m	A/mV/ft	m ² /m	ft ² /ft	100 m ² /km	100 ft ² /mile
6.4	2.5	5.23	0.206	8.62	5.79	122.3	37.27	8.178	26.83	0.199	0.654	1.995	34.56
7.303	2.875	7.01	0.276	11.4	7.66	92.42	28.17	10.8	35.5	0.230	0.753	2.294	39.74
8.9	3.5	5.49	0.216	11.3	7.58	93.41	28.47	10.71	35.13	0.279	0.916	2.793	48.38
11	4.5	6.02	0.237	16.06	10.79	66	20	15	50	0.3591	1.178	3.59	62.2
11	4.5	8.56	0.337	22.29	14.98	47.28	14.41	21.16	69.42	0.3591	1.178	3.59	62.2
16.83	6.625	5.56	0.219	22.28	14.97	47.31	14.42	21.14	69.37	0.5285	1.734	5.287	91.58
16.83	6.625	7.1	0.28	28.23	18.97	37.34	11.38	26.79	87.91	0.5285	1.734	5.287	91.58
16.83	6.625	7.92	0.312	31.36	21.07	33.60	10.24	29.76	97.64	0.5285	1.734	5.287	91.58
16.83	6.625	9.53	0.375	37.25	25.03	28.3	8.62	35.354	115.99	0.5285	1.734	5.287	91.58
16.83	6.625	11.0	0.432	42.53	28.58	24.8	7.55	40.368	132.44	0.5285	1.734	5.287	91.58
21.91	8.625	6.4	0.25	33.28	22.36	31.7	9.65	31.580	103.61	0.6882	2.258	6.8822	119.22
21.91	8.625	7.95	0.313	33.84	22.74	31.1	9.49	32.120	105.38	0.6882	2.258	6.8822	119.22
21.91	8.625	8.18	0.322	42.49	28.55	24.8	7.56	40.33	132.3	0.6882	2.258	6.8822	119.22
21.91	8.625	9.53	0.375	49.17	33.04	21.4	6.53	46.66	153.1	0.6882	2.258	6.8822	119.22
27.31	10.75	6.4	0.25	41.73	28.04	25	7.7	39.606	129.94	0.8577	2.814	8.578	148.6
27.31	10.75	9.27	0.365	60.24	40.48	17.5	5.33	57.174	187.58	0.8577	2.814	8.578	148.6
27.31	10.75	9.53	0.375	61.83	41.55	17.0	5.19	58.686	192.54	0.8577	2.814	8.578	148.6
27.31	10.75	11.1	0.438	71.72	48.19	14.7	4.48	68.065	223.31	0.8577	2.814	8.578	148.6
27.31	10.75	13	0.50	81.46	54.74	12.9	3.94	77.316	253.66	0.8577	2.814	8.578	148.6
32.39	12.75	6.4	0.25	49.68	33.38	21.2	6.46	47.146	154.68	1.017	3.338	10.174	176.24
32.39	12.75	7.14	0.281	55.73	37.45	18.9	5.76	52.895	173.54	1.017	3.338	10.174	176.24
32.39	12.75	7.95	0.313	61.77	41.51	17	5.2	58.628	192.35	1.017	3.338	10.174	176.24
32.39	12.75	9.53	0.375	73.75	49.56	14.3	4.35	70.000	229.66	1.017	3.338	10.174	176.24
32.39	12.75	13	0.50	97.36	65.42	11	3.3	92.400	303.15	1.017	3.338	10.174	176.24
36	14	6.4	0.25	54.63	36.71	26	7.8	39.054	128.13	1.117	3.665	11.171	193.52
36	14	7.92	0.312	67.98	45.68	20.6	6.27	48.597	159.44	1.117	3.665	11.171	193.52
41	16	6.4	0.25	62.58	42.05	22.3	6.81	44.735	146.77	1.277	4.189	12.767	221.17

Table B1: Pipe Data (Continued)

OD		Wall Thickness		Weight		Resistance		Factor		External Area			
cm	in.	mm	in.	kg/m	lb/ft	$\mu\text{ohm/m}$	$\mu\text{ohm/ft}$	A/mV/m	A/mV/ft	m^2/m	ft^2/ft	100 m^2/km	100 ft^2/mile
41	16	6.35	0.250	62.58	42.05	22.3	6.81	44.735	146.77	1.277	4.189	12.770	221.17
41	16	7.92	0.312	77.92	52.36	17.9	5.47	55.705	182.76	1.277	4.189	12.770	221.17
41	16	9.53	0.375	93.13	62.58	15.0	4.58	66.577	218.43	1.277	4.189	12.770	221.17
41	16	16.7	0.656	160.0	107.5	8.76	2.67	114.37	375.22	1.277	4.189	12.770	221.17
46	18	6.35	0.250	70.53	47.39	19.8	6.05	50.417	165.41	1.436	4.712	14.360	248.81
51	20	6.35	0.250	78.47	52.73	17.8	5.43	56.098	184.05	1.596	5.236	15.960	276.46
51	20	7.14	0.281	88.15	59.23	15.9	4.84	63.014	206.74	1.596	5.236	15.960	276.46
51	20	7.92	0.312	84.40	56.71	16.6	5.05	60.332	197.94	1.596	5.236	15.960	276.46
51	20	9.53	0.375	117	78.6	12.0	3.65	83.622	274.35	1.596	5.236	15.960	276.46
56	22	6.35	0.250	86.42	58.07	16.2	4.93	61.780	202.69	1.756	5.760	17.560	304.11
59.373	23.375	9.53	0.375	137.2	92.19	10.2	3.11	98.079	321.78	1.865	6.120	18.650	323.11
59.373	23.375	11.9	0.469	170.7	114.7	8.20	2.50	122.07	400.49	1.865	6.120	18.650	323.11
61	24	7.14	0.281	106.0	71.25	13.2	4.02	75.801	248.69	1.915	6.283	19.150	331.75
61	24	7.92	0.312	117.7	79.06	11.9	3.62	84.110	275.95	1.915	6.283	19.150	331.75
61	24	8.74	0.344	129.2	86.85	10.8	3.30	92.397	303.14	1.915	6.283	19.150	331.75
61	24	10.3	0.406	152.3	102.4	9.19	2.80	108.91	357.31	1.915	6.283	19.150	331.75
61	24	11.9	0.469	175.3	117.8	7.97	2.43	125.33	411.20	1.915	6.283	19.150	331.75
61	24	12.7	0.500	186.8	125.5	7.48	2.28	133.51	438.01	1.915	6.283	19.150	331.75
61	24	15.9	0.625	232.2	156.1	6.04	1.84	166.02	544.68	1.915	6.283	19.150	331.75
66	26	7.24	0.285	117	78.3	12.0	3.66	83.302	273.30	2.075	6.807	20.750	359.40
66	26	7.92	0.312	142.5	95.73	9.81	2.99	101.85	334.14	2.075	6.807	20.750	359.40
66	26	8.26	0.325	132.6	89.12	10.5	3.21	94.811	311.06	2.075	6.807	20.750	359.40
66	26	9.53	0.375	152.73	102.63	9.15	2.79	109.19	358.22	2.075	6.807	20.750	359.40
66	26	12.7	0.500	202.65	136.17	6.89	2.10	144.87	475.29	2.075	6.807	20.750	359.40

Table B1: Pipe Data (Continued)

OD		Wall Thickness		Weight		Resistance		Factor		External Area			
cm	in.	mm	in.	kg/m	lb/ft	μohm/m	μohm/ft	A/mV/m	A/mV/ft	m ² /m	ft ² /ft	100 m ² /km	100 ft ² /mile
76	30	7.92	0.312	147.4	99.08	9.48	2.89	105.41	345.83	2.394	7.854	23.939	414.69
76	30	8.26	0.325	153.12	102.89	9.12	2.78	109.46	359.13	2.394	7.854	23.939	414.69
76	30	8.74	0.344	162.03	108.88	8.63	2.63	115.83	380.03	2.394	7.854	23.939	414.69
76	30	9.1	0.36	169.59	113.96	8.23	2.51	121.24	397.77	2.394	7.854	23.939	414.69
76	30	9.53	0.375	176.57	118.65	7.91	2.41	126.23	414.14	2.394	7.854	23.939	414.69
76	30	10.3	0.406	191.1	128.4	7.32	2.23	136.60	448.17	2.394	7.854	23.939	414.69
76	30	11.1	0.438	205.56	138.13	6.79	2.07	146.95	482.13	2.394	7.854	23.939	414.69
76	30	10	0.50	234.43	157.53	5.97	1.82	167.59	549.84	2.394	7.854	23.939	414.69
91	36	8.74	0.344	194.8	130.9	7.19	2.19	139.26	456.89	2.873	9.425	28.727	497.63
91	36	9.53	0.375	212.33	142.68	6.59	2.01	151.79	498.01	2.873	9.425	28.727	497.63
91	36	10.3	0.406	229.82	154.43	6.10	1.86	164.29	539.02	2.873	9.425	28.727	497.63
91	36	11.9	0.469	264.72	177.88	5.28	1.61	189.24	620.87	2.873	9.425	28.727	497.63
91	36	10	0.50	282.12	189.57	4.95	1.51	201.68	661.68	2.873	9.425	28.727	497.63
91	36	14.3	0.562	316.82	212.89	4.43	1.35	226.49	743.07	2.873	9.425	28.727	497.63
91	36	15.9	0.625	351.41	236.13	3.97	1.21	251.21	824.19	2.873	9.425	28.727	497.63
91	36	17.4	0.687	385.86	259.28	3.61	1.10	275.84	904.99	2.873	9.425	28.727	497.63
107	42.0	9.53	0.375	248.13	166.73	5.64	1.72	177.38	581.95	3.3516	10.996	33.516	580.57
107	42.0	9.9	0.39	257.92	173.31	5.41	1.65	184.38	604.92	3.3516	10.996	33.516	580.57
107	42.0	11.1	0.438	289.3	194.4	4.82	1.47	206.82	678.53	3.3516	10.996	33.516	580.57
107	42.0	10	0.50	329.84	221.64	4.23	1.29	235.80	773.61	3.3516	10.996	33.516	580.57
107	42.0	14.3	0.562	370.1	248.7	3.77	1.15	264.58	868.06	3.3516	10.996	33.516	580.57
107	42.0	15.9	0.625	411.07	276.22	3.41	1.04	293.86	964.12	3.3516	10.996	33.516	580.57
122	48.0	10	0.50	377.52	253.68	3.71	1.13	269.89	885.45	3.8301	12.566	38.301	663.50
122	48.0	15.9	0.625	470.67	316.27	2.99	0.910	336.472	1,103.91	3.8301	12.566	38.301	663.50
122	48.0	19	0.75	563.31	378.52	2.49	0.760	402.699	1,321.19	3.8301	12.566	38.301	663.50

Standard Test Method

Measurement Techniques Related to Criteria for Cathodic Protection on Underground or Submerged Metallic Piping Systems

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Reaffirmed 2002-04-11
Approved 1997-12-22
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ISBN 1-57590-047-5
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Foreword

This NACE International standard test method provides descriptions of the measurement techniques and cautionary measures most commonly used on underground piping to determine whether a specific criterion has been complied with at a test site. This test method includes only those measurement techniques that relate to the criteria or special conditions, such as a net protective current, contained in NACE Standard RP0169.¹ This test method is intended for use by corrosion control personnel concerned with the corrosion of buried underground or submerged piping systems, including oil, gas, water, and similar structures.

The measurement techniques described require that the measurements be made in the field. Because the measurements are obtained under widely varying circumstances of field conditions and pipeline design, this standard is not as prescriptive as those NACE standard test methods that use laboratory measurements. Instead, this standard gives the user latitude to make testing decisions in the field based on the technical facts available.

This standard contains instrumentation and general measurement guidelines. It includes methods for voltage drop considerations when making pipe-to-electrolyte potential measurements and provides guidance to prevent incorrect data from being collected and used.

The measurement techniques provided in this standard were compiled from information submitted by committee members and others with expertise on the subject. Variations or other techniques not included may be equally effective. The complexity and diversity of environmental conditions may require the use of other techniques.

Appendix A contains information on the common types, use, and maintenance of reference electrodes. Appendix B contains information for the net protective current technique, which, while not a criterion, is a useful technique to reduce corrosion. Appendix C contains information regarding the use of coupons to evaluate cathodic protection. While some engineers use these techniques, they are not universally accepted practices. However, there is ongoing research into their use.

The test methods in this standard were originally prepared by NACE Task Group T-10A-3 on Test Methods and Measurement Techniques Related to Cathodic Protection Criteria, a component of Unit Committee T-10A on Cathodic Protection. It was reviewed by Task Group 020 and reaffirmed in 2002 by Specific Technology Group (STG) 35 on Pipelines, Tanks, and Well Casings. This standard is issued by NACE under the auspices of STG 35.

In NACE standards, the terms *shall*, *must*, *should*, and *may* are used in accordance with the definitions of these terms in the *NACE Publications Style Manual*, 4th ed., Paragraph 7.4.1.9. *Shall* and *must* are used to state mandatory requirements. *Should* is used to state that which is considered good and is recommended but is not absolutely mandatory. *May* is used to state that which is considered optional.

NACE International Standard Test Method

Measurement Techniques Related to Criteria for Cathodic Protection on Underground or Submerged Metallic Piping Systems

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Section 1: General

1.1 This standard provides testing procedures to comply with the requirements of a criterion at a test site on a buried or submerged steel, cast iron, copper, or aluminum pipeline.

1.2 The provisions of this standard shall be applied by personnel who have acquired by education and related practical experience the principles of cathodic protection of buried and submerged metallic piping systems.

1.3 Special conditions in which a given test technique is ineffective or only partially effective sometimes exist. Such conditions may include elevated temperatures, disbonded dielectric or thermally insulating coatings, shielding, bacterial attack, and unusual contaminants in the electrolyte. Deviation from this standard may be warranted in specific situations. In such situations corrosion control personnel should be able to demonstrate that adequate cathodic protection has been achieved.

Section 2: Definitions⁽¹⁾

Anode: The electrode of an electrochemical cell at which oxidation occurs. Electrons flow away from the anode in the external circuit. Corrosion usually occurs and metal ions enter the solution at the anode.

Cable: A bound or sheathed group of insulated conductors.

Cathode: The electrode of an electrochemical cell at which reduction is the principal reaction. Electrons flow toward the cathode in the external circuit.

Cathodic Disbondment: The destruction of adhesion between a coating and the coated surface caused by products of a cathodic reaction.

Cathodic Polarization: The change of electrode potential in the active (negative) direction caused by current across the electrode/electrolyte interface. See also *Polarization*.

Cathodic Protection: A technique to reduce the corrosion of a metal surface by making that surface the cathode of an electrochemical cell.

Cathodic Protection Coupon: A metal sample representing the pipeline at the test site, used for cathodic protection testing, and having a chemical composition approximating that of the pipe. The coupon size should be small to avoid excessive current drain on the cathodic protection system.

Coating: A liquid, liquefiable, or mastic composition that, after application to a surface, is converted into a solid protective, decorative, or functional adherent film.

Conductor: A bare or insulated material suitable for carrying electric current.

Corrosion: The deterioration of a material, usually a metal, that results from a reaction with its environment.

Corrosion Potential (E_{corr}): The potential of a corroding surface in an electrolyte relative to a reference electrode under open-circuit conditions (also known as *rest potential*, *open-circuit potential*, or *freely corroding potential*).

Criterion: A standard for assessment of the effectiveness of a cathodic protection system.

Current Density: The current to or from a unit area of an electrode surface.

Electrical Isolation: The condition of being electrically separated from other metallic structures or the environment.

Electrode: A conductor used to establish contact with an electrolyte and through which current is transferred to or from an electrolyte.

Electrode Potential: The potential of an electrode in an electrolyte as measured against a reference electrode. (The electrode potential does not include any resistance losses in potential in either the electrolyte or the external circuit. It represents the reversible work to move a unit charge from the electrode surface through the electrolyte to the reference electrode.)

Electrolyte: A chemical substance containing ions that migrate in an electric field. (For the purpose of this standard, *electrolyte* refers to the soil or liquid, including contained moisture and other chemicals, next to and in contact with a buried or submerged metallic piping system.)

Foreign Structure: Any metallic structure that is not intended as part of a system under cathodic protection.

⁽¹⁾ Definitions in this section reflect common usage among practicing corrosion control personnel and apply specifically to how terms are used in this standard. As much as possible, these definitions are in accord with those in the "NACE Glossary of Corrosion-Related Terms" (Houston, TX: NACE).

Free Corrosion Potential: See *Corrosion Potential*.

Galvanic Anode: A metal that provides sacrificial protection to another metal that is more noble when electrically coupled in an electrolyte. This type of anode is the current source in one type of cathodic protection.

Holiday: A discontinuity in a protective coating that exposes unprotected surface to the environment.

Impressed Current: An electric current supplied by a device employing a power source that is external to the electrode system. (An example is direct current for cathodic protection.)

“Instant Off” Potential: A measurement of a pipe-to-electrolyte potential made without perceptible delay following the interruption of cathodic protection.

Interference: Any electrical disturbance on a metallic structure as a result of stray current.

Isolation: See *Electrical Isolation*.

Long-Line Current: Current through the earth between an anodic and a cathodic area that returns along an underground metallic structure.

Long-Line Current Voltage Drop Error: That voltage drop error in the “off” potential that is caused by current flow in the soil due to potential gradients along the pipe surface.

“Off” or “On”: A condition whereby cathodic protection current is either turned off or on.

Pipe-to-Electrolyte Potential: The potential difference between the pipe metallic surface and electrolyte that is measured with reference to an electrode in contact with the electrolyte. This measurement is commonly termed *pipe-to-soil (P/S)*.

Pipe-to-Soil: See *Pipe-to-Electrolyte Potential*.

Polarization: The change from the open-circuit potential as a result of current across the electrode/electrolyte interface.

Polarized Potential: The potential across the structure/electrolyte interface that is the sum of the corrosion potential and the cathodic polarization.

Potential Gradient: A change in the potential with respect to distance, expressed in millivolts per unit of distance.

Protection Potential: A measured potential meeting the requirements of a cathodic protection criterion.

Reference Electrode: An electrode whose open-circuit potential is constant under similar conditions of

measurement, which is used for measuring the relative potentials of other electrodes.

Resistance to Electrolyte: The resistance of a structure to the surrounding electrolyte.

Reverse-Current Switch: A device that prevents the reversal of direct current through a metallic conductor.

Shielding: Preventing or diverting the cathodic protection current from its intended path to the structure to be protected.

Shorted Pipeline Casing: A casing that is in metallic contact with the carrier pipe.

Side Drain Potential: A potential gradient measured between two reference electrodes, one located over the pipeline and the other located a specified distance lateral to the direction of the pipe.

Sound Engineering Practices: Reasoning exhibited or based on thorough knowledge and experience, logically valid, and having true premises showing good judgment or sense in the application of science.

Stray Current: Current through paths other than the intended circuit.

Telluric Current: Current in the earth that results from geomagnetic fluctuations.

Test Lead: A wire or cable attached to a structure for connection of a test instrument to make cathodic protection potential or current measurements.

Voltage: An electromotive force or a difference in electrode potentials expressed in volts.

Voltage Drop: The voltage across a resistance according to Ohm’s Law.

Voltage Spiking: A momentary surging of potential that occurs on a pipeline when the protective current flow from an operating cathodic protection device is interrupted or applied. This phenomenon is the result of inductive and capacitive electrical characteristics of the system and may be incorrectly recorded as an “off” or “on” pipe-to-electrolyte potential measurement. This effect may last for several hundred milliseconds and is usually larger in magnitude near the connection of the cathodic protection device to the pipeline. An oscilloscope or similar instrument may be necessary to identify the magnitude and duration of the spiking.

Wire: A slender rod or filament of drawn metal. In practice, the term is also used for smaller gauge conductors (size 6 mm² [No. 10 AWG⁽²⁾] or smaller).

⁽²⁾ American Wire Gauge (AWG).

Section 3: Safety Considerations

3.1 Appropriate safety precautions, including the following, shall be observed when making electrical measurements.

3.1.1 Be knowledgeable and qualified in electrical safety precautions before installing, adjusting, repairing, removing, or testing impressed current cathodic protection equipment.

3.1.2 Use properly insulated test lead clips and terminals to avoid contact with unanticipated high voltage (HV). Attach test clips one at a time using a single-hand technique for each connection.

3.1.3 Use caution when long test leads are extended near overhead high-voltage alternating current (HVAC) power lines, which can induce hazardous voltages onto the test leads. High-voltage direct current (HVDC) power lines do not induce voltages under normal operation, but transient conditions may cause hazardous voltages.

3.1.3.1 Refer to NACE Standard RP01772 for additional information about electrical safety.

3.1.4 Use caution when making tests at electrical isolation devices. Before proceeding with further tests, use appropriate voltage detection instruments or voltmeters with insulated test leads to determine whether hazardous voltages may exist.

3.1.5 Avoid testing when thunderstorms are in the area. Remote lightning strikes can create hazardous voltage surges that travel along the pipe under test.

3.1.6 Use caution when stringing test leads across streets, roads, and other locations subject to vehicular and pedestrian traffic. When conditions warrant, use appropriate barricades, flagging, and/or flag persons.

3.1.7 Before entering, inspect excavations and confined spaces to determine that they are safe. Inspections may include shoring requirements for excavations and testing for hazardous atmospheres in confined spaces.

3.1.8 Observe appropriate electrical codes and applicable safety regulations.

Section 4: Instrumentation and Measurement Guidelines

4.1 Cathodic protection electrical measurements require proper selection and use of instruments. Pipe-to-electrolyte potential, voltage drop, potential difference, and similar measurements require instruments that have appropriate voltage ranges. The user should know the capabilities and limitations of the equipment, follow the manufacturer's instruction manual, and be skilled in the use of electrical instruments. Failure to select and use instruments correctly causes errors in cathodic protection measurements.

4.1.1 Analog instruments are usually specified in terms of input resistance or internal resistance. This is usually expressed as ohms per volt of full meter scale deflection.

4.1.2 Digital instruments are usually specified in terms of input impedance expressed as megaohms.

4.2 Factors that may influence instrument selection for field testing include:

- (a) Input impedance (digital instruments);
- (b) Input resistance or internal resistance (analog instruments);
- (c) Sensitivity;
- (d) Conversion speed of analog-to-digital converters used in digital or data logging instruments;
- (e) Accuracy;

- (f) Instrument resolution;
- (g) Ruggedness;
- (h) Alternating current (AC) and radio frequency (RF) signal rejection; and
- (i) Temperature and/or climate limitations.

4.2.1 Some instruments are capable of measuring and processing voltage readings many times per second. Evaluation of the input wave-form processing may be required if an instrument does not give consistent results.

4.2.2 Measurement of pipe-to-electrolyte potentials on pipelines affected by dynamic stray currents may require the use of recording or analog instruments to improve measurement accuracy. Dynamic stray currents include those from electric railway systems, HVDC transmission systems, mining equipment, and telluric currents.

4.3 Instrument Effects on Voltage Measurements

4.3.1 To measure pipe-to-electrolyte potentials accurately, a digital voltmeter must have a high input impedance (high internal resistance, for an analog instrument) compared with the total resistance of the measurement circuit.

4.3.1.1 An input impedance of 10 megaohms or more should be sufficient for a digital meter. An instrument with a lower input impedance may produce valid data if circuit contact errors are considered. One means of making accurate measurements is to use a potentiometer circuit in an analog meter.

4.3.1.2 A voltmeter measures the potential across its terminals within its design accuracy. However, current flowing through the instrument creates measurement errors due to voltage drops that occur in all resistive components of a measurement circuit.

4.3.2 Some analog-to-digital converters used in digital and data logging instruments operate so fast that the instrument may indicate only a portion of the input waveform and thus provide incorrect voltage indications.

4.3.3 Parallax errors on an analog instrument can be minimized by viewing the needle perpendicular to the

face of the instrument on the centerline projected from the needle point.

4.3.4 The accuracy of potential measurements should be verified by using an instrument having two or more input impedances (internal resistance, for analog instruments) and comparing potential values measured using different input impedances. If the measured values are virtually the same, the accuracy is acceptable. Corrections need to be made if measured values are not virtually identical. Digital voltmeters that have a constant input impedance do not indicate a measurement error by changing voltage ranges. An alternative is to use a meter with a potentiometer circuit.

4.4 Instrument Accuracy

4.4.1 Instruments shall be checked for accuracy before use by comparing readings to a standard voltage cell, to another acceptable voltage source, or to another appropriate instrument known to be accurate.

Section 5: Pipe-to-Electrolyte Potential Measurements

5.1 Instruments used to measure AC voltage, direct current (DC) voltage, or other electrical functions usually have one terminal designated "Common" (COM). This terminal either is black in color or has a negative (-) symbol. The positive terminal either is red in color or has a positive (+) symbol. The positive and negative symbols in the meter display indicate the current flow direction through the instrument (Figure 1a). For example, a positive symbol in the meter display indicates current flowing from the positive terminal through the meter to the negative terminal. One instrument test lead is usually black in color and the other red. The black test lead is connected to the negative terminal of the instrument and the red lead to the positive terminal.

5.2 Voltage measurements should be made using the lowest practicable range on the instrument. A voltage measurement is more accurate when it is measured in the upper two-thirds of a range selected for a particular instrument. Errors can occur, for example, when an instrument with a 2-V range is used to measure a voltage of 15 mV. Such a value might be a voltage drop caused by current flowing in a metal pipeline or through a calibrated shunt. A much more accurate measurement would be made using an instrument having a 20-mV range.

5.3 The usual technique to determine the DC voltage across battery terminals, pipeline metal/electrolyte interface, or other DC system is to connect the black test lead to the negative side of the circuit and the red test lead to the positive side of the circuit. When connected in this manner, an analog instrument needle moves in an upscale

(clockwise) direction indicating a positive value with relation to the negative terminal. A digital instrument connected in the same manner displays a digital value, usually preceded by a positive symbol. In each situation the measured voltage is positive with respect to the instrument's negative terminal. (See instrument connections in Figure 1a.)

5.4 The voltage present between a reference electrode and a metal pipe can be measured with a voltmeter. The reference electrode potential is normally positive with respect to ferrous pipe; conversely the ferrous pipe is negative with respect to the reference electrode.

5.5 A pipe-to-electrolyte potential is measured using a DC voltmeter having an appropriate input impedance (or internal resistance, for an analog instrument), voltage range(s), test leads, and a stable reference electrode, such as a saturated copper/copper sulfate (CSE), silver/silver chloride (Ag/AgCl), or saturated potassium chloride (KCl) calomel reference electrode. The CSE is usually used for measurements when the electrolyte is soil or fresh water and less often for salt water. When a CSE is used in a high-chloride environment, the stability (lack of contamination) of the CSE must be determined before the readings may be considered valid. The Ag/AgCl reference electrode is usually used in seawater environments. The saturated KCl calomel electrode is used more often for laboratory work. However, more-rugged, polymer-body, gel-filled saturated KCl calomel electrodes are available, though modifications may be necessary to increase contact area with the environment.

5.6 Meter Polarity

5.6.1 Pipe-to-electrolyte potentials are usually measured by connecting the instrument negative terminal to the pipe and the positive terminal to the reference electrode, which is in contact with the pipe electrolyte. With this connection the instrument indicates that the reference electrode is positive with respect to the pipe. Because the reference electrode has a positive value with respect to the pipe, the pipe voltage is negative with respect to the reference electrode (see Figure 1a). This negative pipe-to-electrolyte potential is the value used for NACE criteria.

5.6.2 Pipe-to-electrolyte potential measurements are sometimes made with the reference electrode connected to the instrument negative terminal and the pipeline to the positive terminal. Figure 1b illustrates this connection.

5.6.2.1 If the instrument is a data logging device, the recorded data may be printed out with a negative symbol unless a polarity reversal occurs.

5.7 The pipe-to-electrolyte potential measurement of a buried pipe should be made with the reference electrode placed close to the metal/electrolyte interface of the pipe. The common practice, however, is to place the reference electrode as close to the pipe as practicable, which is usually at the surface of the earth above the centerline of the pipe. (See Figure 1a.) This measurement includes a combination of the voltage drops associated with the:

- (a) Voltmeter;
- (b) Test leads;
- (c) Reference electrode;
- (d) Electrolyte;
- (e) Coating, if applied;
- (f) Pipe; and
- (g) Pipe metal/electrolyte interface.

5.8 The pipe-to-electrolyte potential measurement as described above is a resultant of the:

- (a) Voltage drop created by current flowing through the electrical resistances of the items listed in Paragraph 5.7; and
- (b) For coated pipe, the influence of coating holidays, depending on their location, number, and size.

5.9 Pipe-to-electrolyte potential measurements made to determine the level of cathodic protection at the test site should consider the following:

- (a) Effectiveness of coatings, particularly those known or suspected to be deteriorated or damaged;
- (b) Bare sections of pipe;
- (c) Bonds to mitigate interference;
- (d) Parallel coated pipelines, electrically connected and polarized to different potentials;
- (e) Shielding;

- (f) Effects of other structures on the measurements;
- (g) History of corrosion leaks and repairs;
- (h) Location of impressed current anodes;
- (i) Unknown, inaccessible, or direct-connected galvanic anodes;
- (j) Location of isolation devices, including high-resistance pipe connections and compression couplings;
- (k) Presence of electrolytes, such as unusual corrosives, chemical spills, extreme soil resistivity changes, acidic waters, and contamination from sewer spills;
- (l) Location of shorted or isolated casings;
- (m) DC interference currents, such as HVDC, telluric, welding equipment, foreign rectifier, mining equipment, and electric railway or transit systems;
- (n) Contacts with other metals or structures;
- (o) Locations where the pipe enters and leaves the electrolyte;
- (p) Areas of construction activity during the pipeline history;
- (q) Underground metallic structures close to or crossing the pipeline;
- (r) Valves and other appurtenances; and
- (s) HVAC overhead power lines.

5.10 Voltage drops other than those across the pipe metal/electrolyte interface shall be considered for valid interpretation of pipe-to-electrolyte voltage measurements made to satisfy a criterion. Measurement errors should be minimized to ensure reliable pipe-to-electrolyte potential measurements.

5.11 The effect of voltage drops on a pipe-to-electrolyte potential measurement can be determined by interrupting all significant current sources and then making the measurement. This measurement is referred to as an "instant-off" potential. The measurement must be made without perceptible delay after current interruption to avoid loss of polarization. The voltage value measured is considered to be the "polarized potential" of the pipe at that location. Because the current interruption may cause a voltage spike, recording the spike as the "instant-off potential" must be avoided. The magnitude and duration of the voltage spike can vary; however, the duration is usually within 0.5 second. The following are examples of when it may not be practical to interrupt all current sources to make the "instant-off potential" measurement.

5.11.1 Galvanic Anodes

5.11.1.1 Galvanic anodes connected directly to the pipe without benefit of aboveground test stations or connections. Interruption requires excavation of the connections.

5.11.2 Impressed Current Systems

5.11.2.1 Galvanic anodes directly connected to piping protected using an impressed current system;

5.11.2.2 Multiple impressed current sources;

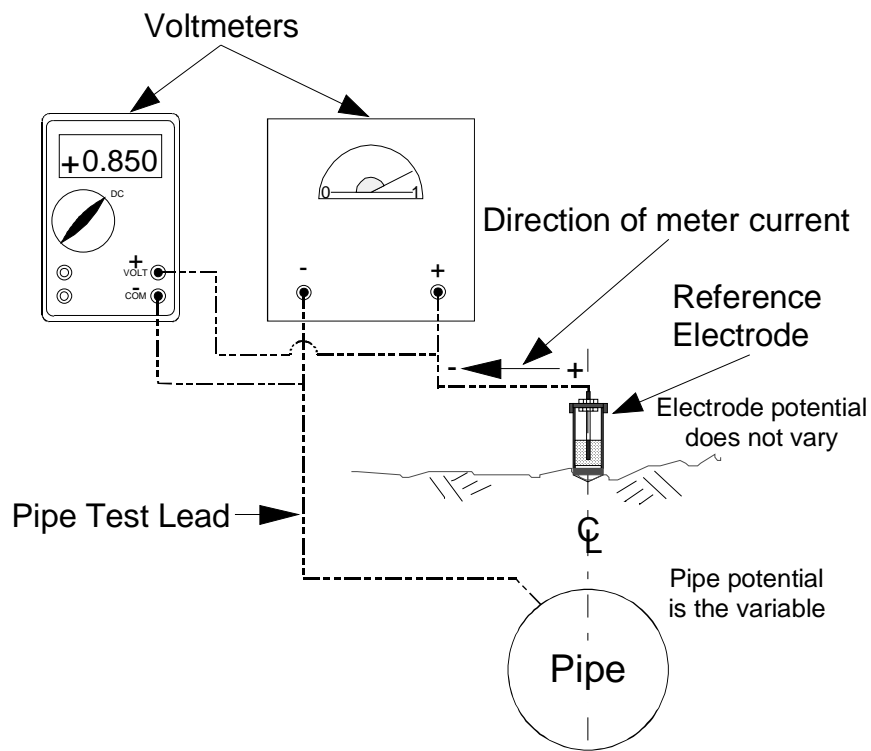


Figure 1a
Instrument Connection

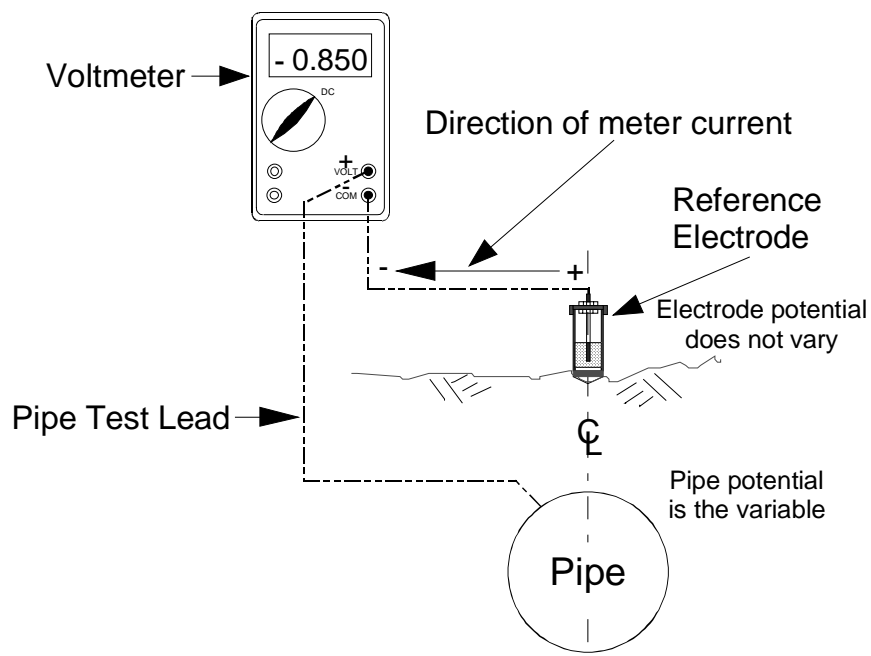


Figure 1b
Alternative Instrument Connection

FIGURE 1
Instrument Connections

5.11.2.3 Impressed current devices on foreign piping; and

5.11.2.4 Numerous cross bonds to parallel pipelines.

5.11.3 Natural and Manmade Stray Currents

5.11.3.1 Telluric currents; and

5.11.3.2 Manmade DC stray currents, such as those from mass transit and mining operations.

5.12 When voltage drops have been evaluated at a test location and the pipe-to-electrolyte potential found to be satisfactory, the "on" pipe-to-electrolyte potential value may be used for monitoring until significant environmental, structural, or cathodic protection system parameters change.

5.12.1 Significant environmental, structural, or cathodic protection system parameter changes may include:

- (a) Replacement or addition of piping;
- (b) Addition, relocation, or deterioration of cathodic protection systems;
- (c) Failure of electrical isolating devices;
- (d) Effectiveness of coatings; and
- (e) Influence of foreign structures.

5.13 After a cathodic protection system is operating, time may be required for the pipe to polarize. This should be considered when measuring the potential at a test site on a newly protected pipe or after reenergizing a cathodic protection device.

Section 6: Causes of Measurement Errors

6.1 Factors that contribute to faulty potential measurements include:

6.1.1 Pipe and instrument test leads

- (a) Broken or frayed wire strands (may not be visible inside the insulation);
- (b) Damaged or defective test lead insulation that allows the conductor to contact wet vegetation, the electrolyte, or other objects;
- (c) Loose, broken, or faulty pipe or instrument connections; and
- (d) Dirty or corroded connection points.

6.1.2 Reference electrode condition and placement

- (a) Contaminated reference electrode solution or rod, and solutions of insufficient quantity or saturation (only laboratory-grade chemicals and distilled water, if water is required, should be used in a reference electrode);
- (b) Reference electrode plug not sufficiently porous to provide a conductive contact to the electrolyte;
- (c) Porous plug contaminated by asphalt, oil, or other foreign materials;
- (d) High-resistance contact between reference electrode and dry or frozen soil, rock, gravel, vegetation, or paving material;
- (e) Reference electrode placed in the potential gradient of an anode;
- (f) Reference electrode positioned in the potential gradient of a metallic structure other than the one with the potential being measured;
- (g) Electrolyte between pipe and disbonded coating causing error due to electrode placement in electrolyte on opposite side of coating;

- (h) Defective permanently installed reference electrode;
- (i) Temperature correction not applied when needed; and
- (j) Photo-sensitive measurement error (in CSE with a clear-view window) due to light striking the electrode electrolyte solution (photovoltaic effect).

6.1.3 Unknown isolating devices, such as unbonded tubing or pipe compression fittings, causing the pipe to be electrically discontinuous between the test connection and the reference electrode location.

6.1.4 Parallel path inadvertently established by test personnel contacting instrument terminals or metallic parts of the test lead circuit, such as test lead clips and reference electrodes, while a potential measurement is being made.

6.1.5 Defective or inappropriate instrument, incorrect voltage range selection, instrument not calibrated or zeroed, or a damp instrument sitting on wet earth.

6.1.6 Instrument having an analog-to-digital converter operating at such a fast speed that the voltage spikes produced by current interruption are indicated instead of the actual "on" and "off" values.

6.1.7 Polarity of the measured value incorrectly observed.

6.1.8 Cathodic protection current-carrying conductor used as a test lead for a pipe potential measurement.

6.1.9 Interference

6.1.9.1 Electromagnetic interference or induction resulting from AC power lines or radio frequency transmitters inducing test lead and/or instrument errors. This condition is often indicated by a fuzzy, fluctuating, or blurred pointer movement on an analog instrument or erratic displays on digital voltmeters. A DC voltmeter must have sufficient AC rejection capability, which can be determined by referring to the manufacturer's specification.

6.1.9.2 Telluric or stray DC currents flowing through the earth and piping.

6.2 Reference electrode contact resistance is reduced by:

6.2.1 Soil moisture—If the surface soil is so dry that the electrical contact of the reference electrode with the

electrolyte is impaired, the soil around the electrode may be moistened with water until the contact is adequate.

6.2.2 Contact surface area—Contact resistance may be reduced by using a reference electrode with a larger contact surface area.

6.2.3 Frozen soil—Contact resistance may be reduced by removing the frozen soil to permit electrode contact with unfrozen soil.

6.2.4 Concrete or asphalt-paved areas—Contact resistance may be reduced by drilling through the paving to permit electrode contact with the soil.

Section 7: Voltage Drops Other Than Across the Pipe Metal/Electrolyte Interface

7.1 Voltage drops that are present when pipe-to-electrolyte potential measurements are made occur in the following:

7.1.1 Measurement Circuit—The voltage drop other than across the pipe metal/electrolyte interface in the measurement circuit is the sum of the individual voltage drops caused by the meter current flow through individual resistances that include:

- (a) Instrument test lead and connection resistances;
- (b) Reference electrode internal resistance;
- (c) Reference electrode-to-electrolyte contact resistance;
- (d) Coating resistance;
- (e) Pipe metallic resistance;
- (f) Electrolyte resistance;
- (g) Analog meter internal resistance; and
- (h) Digital meter internal impedance.

A measurement error occurs if the analog meter internal resistance or the digital meter internal impedance is not several orders of magnitude higher than the sum of the other resistances in the measurement circuit.

7.1.2 Pipe—Current flowing within the pipe wall creates a voltage drop. This voltage drop and the direction of the current shall be considered when the reference electrode is not near the pipe connection and significant current is conducted by the pipe. Consideration is needed because an error in the pipe-to-electrolyte potential measurement will occur if the pipe current causes a significant voltage drop. Current directed to the pipe connection from the reference electrode causes the measured potential to be more negative by the amount of the pipe current voltage drop (see Figure 2a). Conversely, the potential is less negative by that amount if the pipe current direction is

from the pipe connection to the reference electrode (see Figure 2b).

7.1.3 Electrolyte—When a pipe-to-electrolyte potential is measured with cathodic protection current applied, the voltage drop in the electrolyte between the reference electrode and the metal/electrolyte interface shall be considered. Measurements taken close to sacrificial or impressed current anodes can contain a large voltage drop. Such a voltage drop can consist of, but is not limited to, the following:

- (a) A voltage drop caused by current flowing to coating holidays when the line is coated; and
- (b) A voltage drop caused by large voltage gradients in the electrolyte that occur near operating anodes (sometimes termed "raised earth effect").

7.1.3.1 Testing to locate galvanic anodes by moving the reference electrode along the centerline of the line may be necessary when the locations are not known.

7.1.4 Coatings—Most coatings provide protection to the pipe by reducing the pipe surface contact with the environment. Due to the relative ionic impermeability of coatings, they resist current flow. While the insulating ability of coatings reduces the current required for cathodic protection, coatings are not impervious to current flowing through them. Current flow through the coating causes a voltage drop that is greater than when the pipe is bare, under the same environmental conditions.

7.2 Specialized equipment that uses various techniques to measure the impressed current wave form and to calculate a pipe-to-electrolyte potential free of voltage drop is

available. This equipment may minimize problems resulting from spiking effects, drifting of interrupters, and current from other DC sources.

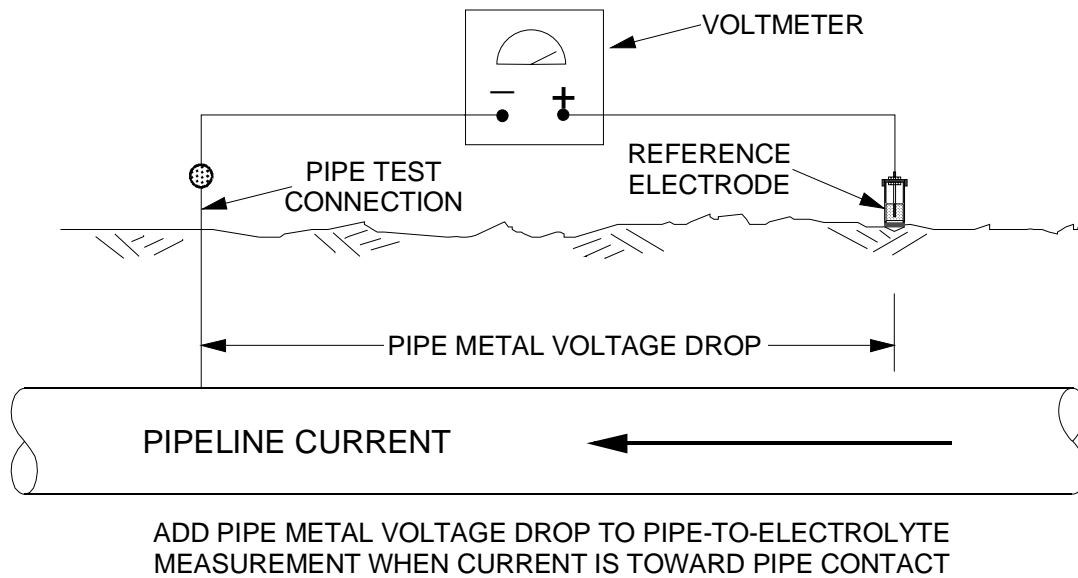


Figure 2a
Correction When Pipeline Current Flows Toward Pipe Test Connection

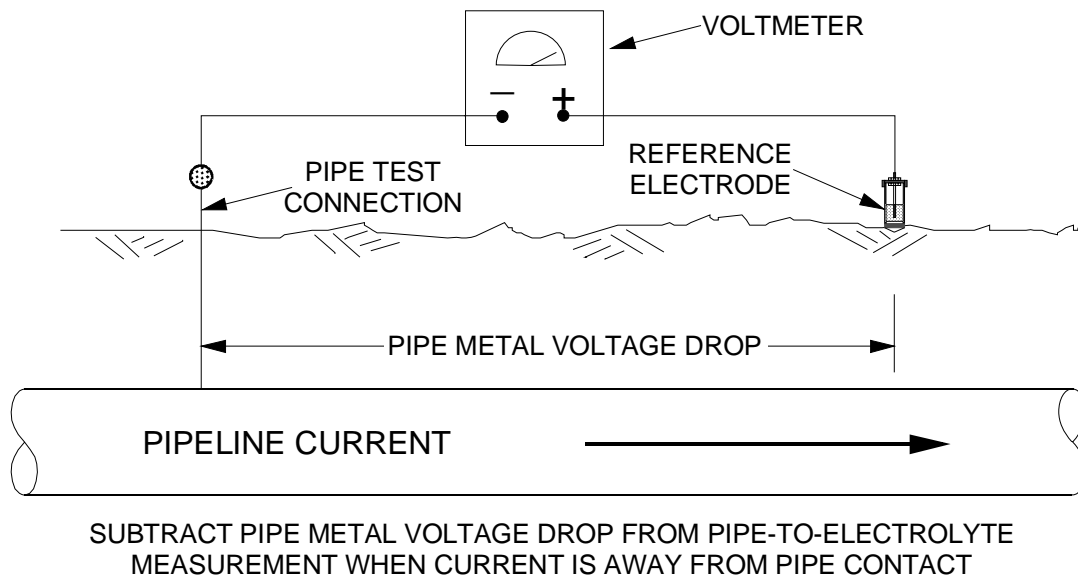


Figure 2b
Correction When Pipeline Current Flows Away from Pipe Test Connection

FIGURE 2
Pipe-to-Electrolyte Potential Corrections for Pipeline Current Flow

Section 8: Test Method 1—Negative 850 mV Pipe-to-Electrolyte Potential of Steel and Cast Iron Piping with Cathodic Protection Applied

8.1 Scope

Test Method 1 describes a procedure to assess the adequacy of cathodic protection on a steel or cast iron pipeline according to the criterion stated in NACE Standard RP0169,¹ Paragraph 6.2.2.1.1:

A negative (cathodic) potential of at least 850 mV with the cathodic protection applied. This potential is measured with respect to a saturated copper/copper sulfate reference electrode (CSE) contacting the electrolyte. Voltage drops other than those across the structure-to-electrolyte boundary must be considered for valid interpretation of this voltage measurement.

NOTE: Consideration is understood to mean the application of sound engineering practice in determining the significance of voltage drops by methods such as:

- (a) Measuring or calculating the voltage drop(s);
- (b) Reviewing the historical performance of the cathodic protection system;
- (c) Evaluating the physical and electrical characteristics of the pipe and its environment; and
- (d) Determining whether there is physical evidence of corrosion.

8.2 General

8.2.1 Cathodic protection current shall remain “on” during the measurement process. This potential is commonly referred to as the “on” potential.

8.2.2 Test Method 1 measures the pipe-to-electrolyte potential as the sum of the polarized potential and any voltage drops in the circuit. These voltage drops include those through the electrolyte and pipeline coating from current sources such as impressed current, galvanic anodes, and telluric effects.

8.2.3 Because voltage drops other than those across the pipe metal/electrolyte interface may be included in this measurement, these drops shall be considered, as discussed in Paragraph 8.6.

8.3 Comparison with Other Methods

8.3.1 Advantages

- (a) Minimal equipment, personnel, and vehicles are required; and
- (b) Less time is required to make measurements.

8.3.2 Disadvantages

- (a) Potential measured includes voltage drops other than those across the pipe metal/electrolyte interface; and
- (b) Meeting the requirements for considering the significance of voltage drops (see Paragraph 8.6) can result in added time to assess adequacy of cathodic protection at the test site.

8.4 Basic Test Equipment

8.4.1 Voltmeter with adequate input impedance. Commonly used digital instruments have a nominal impedance of 10 megaohms. An analog instrument with an internal resistance of 100,000 ohms per volt may be adequate in certain circumstances in which the circuit resistance is low. A potentiometer circuit may be necessary in other instances.

8.4.2 Two color-coded meter leads with clips for connection to the pipeline and reference electrode.

8.4.3 Reference Electrode

8.4.3.1 CSE.

8.4.3.2 Other standard reference electrodes may be substituted for the CSE. These reference electrodes are described in Appendix A, Paragraph A2.

8.5 Procedure

8.5.1 Before the test, verify that cathodic protection equipment has been installed and is operating properly. Time should be allowed for the pipeline potentials to reach polarized values.

8.5.2 Determine the location of the site to be tested. Selection of a site may be based on:

- (a) Location accessible for future monitoring;
- (b) Other protection systems, structures, and anodes that may influence the pipe-to-electrolyte potential;
- (c) Electrical midpoints between protective devices;
- (d) Known location of an ineffective coating if the line is coated; and
- (e) Location of a known or suspected corrosive environment.

8.5.3 Make electrical contact between the reference electrode and the electrolyte at the test site, directly over the centerline of the pipeline or as close to it as is practicable.

8.5.4 Connect the voltmeter to the pipeline and reference electrode as described in Paragraph 5.6.

8.5.5 Record the pipe-to-electrolyte potential and its polarity with respect to the reference electrode.

8.6 Considering the Significance of Voltage Drops for Valid Interpretation of the Criterion

8.6.1 The significance of voltage drops can be considered by:

8.6.1.1 Comparing historical levels of cathodic protection with physical evidence from the pipeline to determine whether corrosion has occurred.

8.6.1.2 Comparing soil corrosiveness with physical evidence from the pipeline to determine whether corrosion has occurred.

8.6.2 Physical evidence of corrosion is determined by evaluating items such as:

- (a) Leak history data;

- (b) Buried pipeline inspection report data regarding locations of coating failures, localized conditions of more-corrosive electrolyte, or substandard cathodic protection levels have been experienced; and/or
- (c) Verification of in-line inspection-tool metal loss indications by follow-up excavation of anomalies and inspection of the pipe external surface.

8.6.3 Cathodic protection shall be judged adequate at the test site if:

- (a) The pipe-to-electrolyte potential measurement is negative 850 mV, or more negative, with respect to a CSE; and
- (b) The significance of voltage drops has been considered by applying the principles described in Paragraphs 8.6.1 or 8.6.2.

8.7 Monitoring

When the significance of a voltage drop has been considered at the test site, the measured potentials may be used for monitoring unless significant environmental, structural, coating integrity, or cathodic protection system parameters have changed.

Section 9: Test Method 2—Negative 850 mV Polarized Pipe-to-Electrolyte Potential of Steel and Cast Iron Piping

9.1 Test Method 2 describes the most commonly used test method to satisfy this criterion (see Paragraph 9.2). This method uses current interruption to determine whether cathodic protection is adequate at the test site according to the criterion.

9.2 Scope

This method uses an interrupter(s) to eliminate the cathodic protection system voltage drop from the pipe-to-electrolyte potential measurement for comparison with the criterion stated in NACE Standard RP0169,¹ Paragraph 6.2.2.1.2:

A negative polarized potential of at least 850 mV relative to a saturated copper/copper sulfate reference electrode (CSE).

9.3 General

9.3.1 Interrupting the known cathodic protection current source(s) eliminates voltage drops associated with the protective currents being interrupted. However, significant voltage drops may also occur because of currents from other sources, as discussed in Section 7.

9.3.2 To avoid significant depolarization of the pipe, the “off” period should be limited to the time necessary

to make an accurate potential measurement. The “off” period is typically less than 3 seconds.

9.3.3 The magnitude and duration of a voltage spike caused by current interruption can vary, but the duration is typically within 0.5 second. After the current is interrupted, the time elapsed until the measurement is recorded should be long enough to avoid errors caused by voltage spiking. On-site measurements with appropriate instruments may be necessary to determine the duration and magnitude of the spiking.

9.3.4 Current sources that can affect the accuracy of this test method include the following:

- (a) Unknown, inaccessible, or direct-connected galvanic anodes;
- (b) Cathodic protection systems on associated piping or foreign structures;
- (c) Electric railway systems;
- (d) HVDC electric power systems;
- (e) Telluric currents;
- (f) Galvanic, or bimetallic, cells;
- (g) DC mining equipment;
- (h) Parallel coated pipelines, electrically connected and polarized to different potentials;
- (i) Uninterrupted current sources;
- (j) Unintentional connections to other structures or bonds to mitigate interference; and
- (k) Long-line currents.

9.4 Comparison with Other Methods

9.4.1 Advantages

(a) Voltage drops associated with the protective currents being interrupted are eliminated.

9.4.2 Disadvantages

- (a) Additional equipment is required;
- (b) Additional time, personnel, and vehicles may be required to set up equipment and to make pipe-to-electrolyte potential measurements; and
- (c) Test results are difficult or impossible to analyze when stray currents are present or direct-connected galvanic anodes or foreign impressed current devices are present and cannot be interrupted.

9.5 Basic Test Equipment

9.5.1 Voltmeter with adequate input impedance. Commonly used digital instruments have a nominal impedance of 10 megohms. An analog instrument with an internal resistance of 100,000 ohms per volt may be adequate in certain circumstances in which the circuit resistance is low. A potentiometer circuit may be necessary in other instances.

9.5.2 Two color-coded meter leads with clips for connection to the pipeline and reference electrode.

9.5.3 Sufficient current interrupters to interrupt influential cathodic protection current sources simultaneously.

9.5.4 Reference electrode

9.5.4.1 CSE.

9.5.4.2 Other standard reference electrodes may be substituted for the CSE. These reference electrodes are described in Appendix A, Paragraph A2.

9.6 Procedure

9.6.1 Before the test, verify that cathodic protection equipment has been installed and is operating properly. Time should be allowed for the pipeline potentials to reach polarized values.

9.6.2 Install and place in operation necessary interrupter equipment in all significant DC sources

protecting the pipe at the test site, and place in operation with a synchronized and/or known "off" and "on" cycle. The "off" cycle should be kept as short as possible but still long enough to read a polarized pipe-to-electrolyte potential after any "spike" as shown in Figure 3a has collapsed.

9.6.3 Determine the location of the site to be tested. Selection of a site may be based on:

- (a) Location accessible for future monitoring;
- (b) Other protection systems, structures, and anodes that may influence the pipe-to-electrolyte potential;
- (c) Electrical midpoints between protection devices;
- (d) Known location of an ineffective coating when the pipeline is coated; and
- (e) Location of a known or suspected corrosive environment.

9.6.4 Make electrical contact between the reference electrode and the electrolyte at the test site, directly over the centerline of the pipeline or as close to it as is practicable.

9.6.5 Connect voltmeter to the pipeline and reference electrode as described in Paragraph 5.6.

9.6.5.1 If spiking may be present, use an appropriate instrument, such as an oscilloscope or high-speed recording device, to verify that the measured values are not influenced by a voltage spike.

9.6.6 Record the pipe-to-electrolyte "on" and "off" potentials and their polarities with respect to the reference electrode.

9.7 Evaluation of Data

Cathodic protection shall be judged adequate at the test site if the polarized pipe-to-electrolyte potential is negative 850 mV, or more negative, with respect to a CSE.

9.8 Monitoring

When the polarized pipe-to-electrolyte potential has been determined to equal or exceed a negative 850 mV, the pipeline "on" potential may be used for monitoring unless significant environmental, structural, coating integrity, or cathodic protection system parameters have changed.

Section 10: Test Method 3—100 mV Cathodic Polarization of Steel, Cast Iron, Aluminum, and Copper Piping

10.1 Test Method 3 describes the use of either pipeline polarization decay or pipeline polarization formation to determine whether cathodic protection is adequate at the test site according to the criterion. Consequently, this test method consists of two mutually independent parts, Test Methods 3a and 3b, that describe the procedures for testing. Cathodic polarization curves for Test Methods 3a and 3b are shown in Figure 3. These are schematic drawings of generic polarization decay and formation.

10.2 Test Method 3a — Use of Pipeline Polarization Decay (Figure 3a)

10.2.1 Scope

This method uses pipeline polarization decay to assess the adequacy of cathodic protection on a steel, cast iron, aluminum, or copper pipeline according to the criterion stated in NACE Standard RP0169,¹ Paragraph 6.2.2.1.3, 6.2.3.1, or 6.2.4.1 (depending on the pipe metal). The paragraph below states Paragraph 6.2.2.1.3:

The following criterion shall apply: A minimum of 100 mV of cathodic polarization between the structure surface and a stable reference electrode contacting the electrolyte. The formation or decay of polarization can be measured to satisfy this criterion.

10.2.2 General

10.2.2.1 Interrupting the known cathodic protection source(s) eliminates voltage drops associated with the protective current(s) being interrupted.

10.2.2.2 Other current sources that can affect the accuracy of this test method include the following:

- (a) Unknown, inaccessible, or direct-connected galvanic anodes;
- (b) Cathodic protection systems on associated piping or foreign structures;
- (c) Electric railway systems;
- (d) HVDC electric power systems;
- (e) Telluric currents;
- (f) Galvanic, or bimetallic, cells;
- (g) DC mining equipment;
- (h) Parallel coated pipelines, electrically connected and polarized to different potentials;
- (i) Uninterrupted current sources;
- (j) Unintentional connections to other structures or bonds to mitigate interference; and
- (k) Long-line currents.

10.2.2.3 The magnitude and duration of a voltage spike caused by current interruption can vary, but the duration is typically within 0.5 second. After the current is interrupted, the time elapsed until the measurement is recorded should be long enough to avoid errors caused by voltage spiking. On-site measurements with appropriate instruments may be necessary to determine the duration and magnitude of the spiking.

10.2.3 Comparison with Other Methods

10.2.3.1 Advantages

- (a) This method is especially useful for bare or ineffectively coated pipe; and
- (b) This method is advantageous when corrosion potentials may be low (for example, 500 mV or less negative) and/or the current required to meet a negative 850 mV polarized potential criterion would be considered excessive.

10.2.3.2 Disadvantages

- (a) Additional equipment is required;
- (b) Additional time, personnel, and vehicles may be required to set up equipment and to make pipe-to-electrolyte potential measurements; and
- (c) Test results are difficult or impossible to analyze when direct-connected galvanic anodes or foreign impressed current devices are present and cannot be interrupted, or when stray currents are present.

10.2.4 Basic Test Equipment

10.2.4.1 Voltmeter with adequate input impedance. Commonly used digital instruments have a nominal impedance of 10 megaohms. An analog instrument with an internal resistance of 100,000 ohms per volt may be adequate in certain circumstances in which the circuit resistance is low. A potentiometer circuit may be necessary in other instances.

10.2.4.1.1 Recording voltmeters can be useful to record polarization decay.

10.2.4.2 Two color-coded meter leads with clips for connection to the pipeline and reference electrode.

10.2.4.3 Sufficient current interrupters to interrupt influential cathodic protection current sources simultaneously.

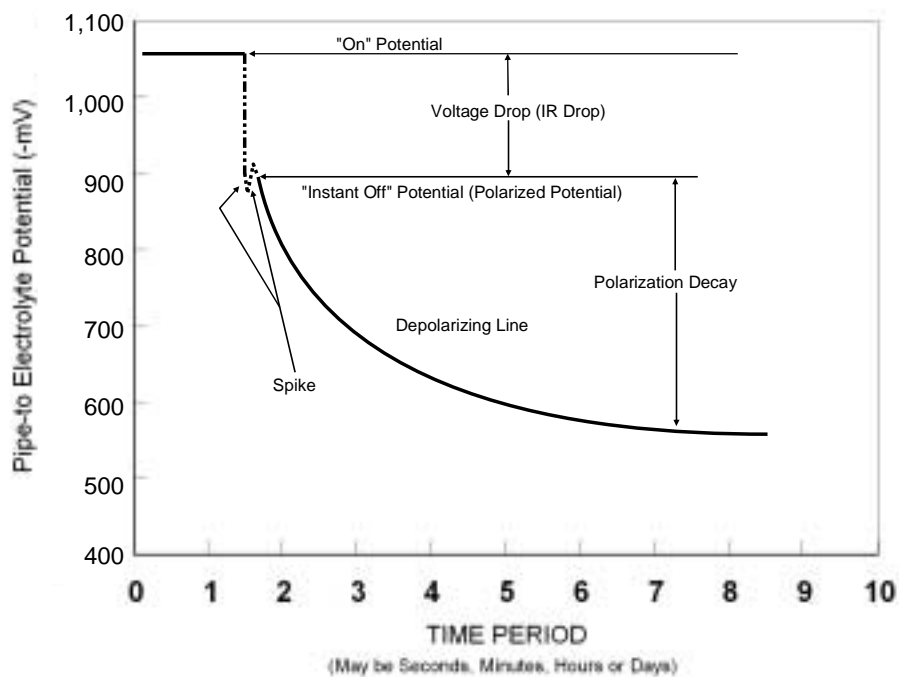


Figure 3a
Polarization Decay

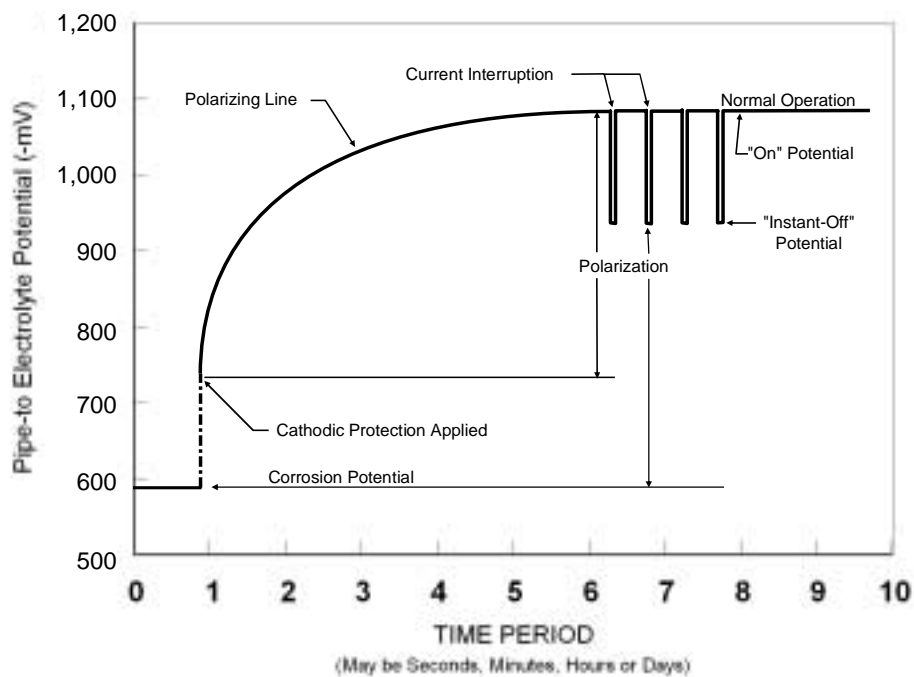


Figure 3b
Polarization Formation

FIGURE 3
Cathodic Polarization Curves

10.2.4.4 Reference electrode

10.2.4.4.1 CSE.

10.2.4.4.2 Other standard reference electrodes may be substituted for the CSE. These reference electrodes are described in Appendix A, Paragraph A2.

10.2.5 Procedure

10.2.5.1 Before the test, verify that cathodic protection equipment has been installed and is operating properly. Time should be allowed for the pipeline potentials to reach polarized values.

10.2.5.2 Install and place in operation necessary interrupter equipment in all significant DC sources protecting the pipe at the test site, and place in operation with a synchronized and/or known "off" and "on" cycle. The "off" cycle should be kept as short as possible but still long enough to read a polarized pipe-to-electrolyte potential after any "spike" as shown in Figure 3a has collapsed.

10.2.5.3 Determine the location of the site to be tested. Selection of a site may be based on:

- (a) Location accessible for future monitoring;
- (b) Other protection systems, structures, and anodes that may influence the pipe-to-electrolyte potential;
- (c) Electrical midpoints between protection devices;
- (d) Known location of an ineffective coating if the pipeline is coated; and
- (e) Location of a known or suspected corrosive environment.

10.2.5.4 Make electrical contact between the reference electrode and the electrolyte at the test site, directly over the centerline of the pipeline or as close to it as is practicable.

10.2.5.4.1 Identify the location of the electrode to allow it to be returned to the same location for subsequent tests.

10.2.5.5 Connect the voltmeter to the pipeline and reference electrode as described in Paragraph 5.6.

10.2.5.5.1 If spiking may be present, use an appropriate instrument, such as an oscilloscope or high-speed recording device, to verify that the measured values are not influenced by a voltage spike.

10.2.5.6 Measure and record the pipe-to-electrolyte "on" and "instant off" potentials and their polarities with respect to the reference electrode.

10.2.5.6.1 The "instant off" pipe-to-electrolyte potential is the "baseline" potential from which the polarization decay is calculated.

10.2.5.7 Turn off sufficient cathodic protection current sources that influence the pipe at the test site until at least 100 mV cathodic polarization decay has been attained.

10.2.5.7.1 Continue to measure and record the pipe-to-electrolyte potential until it either:

- (a) Has become at least 100 mV less negative than the "off" potential; or
- (b) Has reached a stable depolarized level.

10.2.5.7.2 Measurements shall be made at sufficiently frequent intervals to avoid attaining and remaining at a corrosion potential for an unnecessarily extended period.

10.2.5.7.3 When extended polarization decay time periods are anticipated, it may be desirable to use recording voltmeters to determine when adequate polarization decay or a corrosion potential has been attained.

10.2.6 Evaluation of Data

Cathodic protection shall be judged adequate at the test site if 100 mV or more of polarization decay is measured with respect to a standard reference electrode.

10.2.7 Monitoring

When at least 100 mV or more of polarization decay has been measured, the pipeline "on" potential at the test site may be used for monitoring unless significant environmental, structural, coating integrity, or cathodic protection system parameters have changed.

10.3 Test Method 3b—Use of Pipeline Polarization Formation (Figure 3b)

10.3.1 Scope

This method provides a procedure using the formation of polarization to assess the adequacy of cathodic protection at a test site on steel, cast iron, aluminum, or copper piping according to the criteria stated in NACE Standard RP0169,¹ Paragraphs 6.2.2.1.3, 6.2.3.1, or 6.2.4.1 (depending on the pipe metal). The paragraph below states Paragraph 6.2.2.1.3:

The following criterion shall apply: A minimum of 100 mV of cathodic polarization between the structure surface and a stable reference electrode contacting the electrolyte. The formation or decay of polarization can be measured to satisfy this criterion.

10.3.2 General

Ferrous, aluminum, and copper pipelines may be adequately cathodically protected if applying cathodic protection causes a polarization change of 100 mV or more with respect to a reference potential.

10.3.2.1 Current sources that can affect the accuracy of this test method include the following:

- (a) Unknown, inaccessible, or direct-connected galvanic anodes;
- (b) Cathodic protection systems on associated piping or foreign structures;
- (c) Electric railway systems;
- (d) HVDC electric power systems;
- (e) Telluric currents;
- (f) Galvanic, or bimetallic, cells;
- (g) DC mining equipment;
- (h) Parallel coated pipelines, electrically connected and polarized to different potentials;
- (i) Uninterrupted current sources;
- (j) Unintentional connections to other structures or bonds to mitigate interference; and
- (k) Long-line currents.

10.3.3 Comparison with Other Methods

10.3.3.1 Advantages

- (a) This method is especially useful for bare or ineffectively coated pipe; and
- (b) This method is advantageous when corrosion potentials may be low (for example, 500 mV or less negative) and/or the current required to meet a negative 850 mV potential criterion would be considered excessive.

10.3.3.2 Disadvantages

- (a) Additional equipment is required;
- (b) Additional time, personnel, and vehicles may be required to set up equipment and to make the pipe-to-electrolyte potential measurements; and
- (c) Test results are difficult or impossible to analyze when stray currents are present or when direct-connected galvanic anodes or foreign impressed currents are present and cannot be interrupted.

10.3.4 Basic Test Equipment

10.3.4.1 Voltmeter with adequate input impedance. Commonly used digital instruments have a nominal impedance of 10 megaohms. An analog instrument with an internal resistance of 100,000 ohms per volt may be adequate in certain circumstances in which the circuit resistance is low. A potentiometer circuit may be necessary in other instances.

10.3.4.2 Two color-coded meter leads with clips for connection to the pipeline and reference electrode.

10.3.4.3 Sufficient current interrupters to interrupt influential cathodic protection current sources simultaneously.

10.3.4.4 Reference electrode

10.3.4.4.1 CSE.

10.3.4.4.2 Other standard reference electrodes may be substituted for the CSE. These reference electrodes are described in Appendix A, Paragraph A2.

10.3.5 Procedure

10.3.5.1 Before the test, verify that cathodic protection equipment has been installed but is not operating.

10.3.5.2 Determine the location of the site to be tested. Selection of a site may be based on:

- (a) Location accessible for future monitoring;
- (b) Other protection systems, structures, and anodes that may influence the pipe-to-electrolyte potential;
- (c) Electrical midpoints between protection devices;
- (d) Known location of an ineffective coating if the line is coated; and
- (e) Location of a known or suspected corrosive environment.

10.3.5.3 Make electrical contact between the reference electrode and the electrolyte at the test site, directly over the centerline of the pipeline or as close to it as is practicable.

10.3.5.3.1 Identify the location of the electrode to allow it to be returned to the same location for subsequent tests.

10.3.5.4 Connect the voltmeter to the pipeline and reference electrode as described in Paragraph 5.6.

10.3.5.5 Measure and record the pipe-to-electrolyte corrosion potential and its polarity with respect to the reference electrode.

10.3.5.5.1 This potential is the value from which the polarization formation is calculated.

10.3.5.6 Apply the cathodic protection current. Time should be allowed for the pipeline potentials to reach polarized values.

10.3.5.7 Install and place in operation necessary interrupter equipment in all significant DC sources protecting the pipe at the test site, and place in operation with a synchronized and/or known "off" and "on" cycle. The "off" cycle should be kept as short as possible but still long enough to read a polarized pipe-to-electrolyte potential after any "spike" as shown in Figure 3a has collapsed.

10.3.5.8 Measure and record the pipe-to-electrolyte "on" and "off" potentials and their polarities with respect to the reference electrode. The difference between the "off" potential and the corrosion potential is the amount of polarization formation.

10.3.5.8.1 If spiking may be present, use an appropriate instrument, such as an

oscilloscope or high-speed recording device, to verify that the measured values are not influenced by a voltage spike.

10.3.6 Evaluation of Data

Cathodic protection shall be judged adequate if 100 mV or more of polarization formation is measured with respect to a standard reference electrode.

10.3.7 Monitoring

When at least 100 mV or more of polarization formation has been measured, the pipeline "on" potential may be used for monitoring unless significant environmental, structural, coating integrity, or cathodic protection system parameters have changed.

References

1. NACE Standard RP0169 (latest revision), "Control of External Corrosion on Underground or Submerged Metallic Piping Systems" (Houston, TX: NACE).
2. NACE Standard RP0177 (latest revision), "Mitigation of Alternating Current and Lightning Effects on Metallic Structures and Corrosion Control Systems" (Houston, TX: NACE).
3. F.J. Ansuini, J.R. Dimond, "Factors Affecting the Accuracy of Reference Electrodes," *MP* 33, 11 (1994), p. 14.
4. NACE Publication 35201 (latest revision), "Technical Report on the Application and Interpretation of Data from External Coupons Used in the Evaluation of Cathodically Protected Metallic Structures" (Houston, TX: NACE).

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Appendix A: Reference Electrodes

A1 Pipeline metals have unstable electrical potentials when placed in an electrolyte such as soil or water. However, a half-cell that has a stable, electrochemically reversible potential characterized by a single, identifiable half-cell reaction is a reference electrode. The stability of a reference electrode makes it useful as an electrical reference point or benchmark for measuring the potential of another metal in soil or water. When connected by a voltmeter to another metal in soil or water, the reference electrode becomes one half of a corrosion cell. The reference electrodes used for measuring potentials on buried or submerged pipelines have voltage values that are normally positive with respect to steel.

A2 Pipeline potentials are usually measured using either a saturated copper/copper sulfate (CSE), a silver/silver chloride (Ag/AgCl), or a saturated potassium chloride (KCl) calomel reference electrode. CSEs are usually used for measurements when the electrolyte is soil or fresh water, and less often for salt water. When a CSE is used in a high-chloride environment, the stability (i.e., lack of contamination) of the electrode must be determined before the readings may be considered valid. Ag/AgCl reference electrodes are usually used for seawater environments. The KCl calomel electrodes are more often used for laboratory work because they are generally less rugged, unless specially constructed, than the other two reference electrodes.

A2.1 The voltage equivalents (at 25°C [77°F]) to negative 850 mV referred to a CSE are:

A2.1.1 Ag/AgCl seawater reference electrode used in 25 ohm-cm seawater: -800 mV,³ and

A2.1.2 Saturated KCl calomel reference electrode: -780 mV.

A2.2 A CSE is composed of a pure copper rod immersed in a saturated solution of distilled water and copper sulfate (CuSO₄). The pure copper rod extends from one end of the reference electrode, providing a means of connection to a voltmeter. The other end of the reference electrode has a porous plug that is used

to make an electrical contact with the pipeline electrolyte. Undissolved CuSO₄ crystals in the reference electrode should always be visible to ensure the solution is saturated. The reference is reasonably accurate (within 5 mV when measured against a reference electrode known to be free of contamination). The advantages of this reference electrode are low cost and ruggedness.

A2.3 Ag/AgCl reference electrodes are used in marine and soil environments. The construction and the electrode potential vary with the application and with relation to the potential of a CSE reference electrode. The electrolytes involved may be natural seawater, saturated KCl, or other concentrations of KCl. The user shall utilize the manufacturer's recommendations and potential values for the type of Ag/AgCl cell used. The Ag/AgCl reference electrode has a high accuracy (typically less than 2 mV when handled and maintained correctly) and is very durable.

A2.4 A saturated KCl calomel reference electrode for laboratory use is composed of a platinum wire in contact with a mercury/mercurous chloride mixture contacting a saturated KCl solution—enclosed in a glass container, a voltmeter connection on one end, and a porous plug on the other end for contact with the pipeline electrolyte. For field use a more-rugged, polymer-body, gel-filled KCl calomel electrode is available, though modifications may be necessary to increase contact area with the environment. The presence of mercury in this electrode makes it environmentally less desirable for field use.

A2.5 In addition to these standard reference electrodes, an alternative metallic material or structure may be used in place of the saturated CSE if the stability of its electrode potential is ensured and if its voltage equivalent referred to a CSE is established.

A2.6 A permanently installed reference electrode may be used; however, whether it is still accurate should be determined.

A3 It is good practice to verify the accuracy of reference electrodes used in the field by comparing them with a carefully prepared master reference electrode that, to avoid contamination, is never used for field measurements. The accuracy of a field reference electrode can be verified by placing it along with the master reference electrode in a common solution, such as fresh water, and measuring the

voltage difference between the two electrodes. A maximum voltage difference of 5 mV between a master reference electrode and another reference electrode of the same type is usually satisfactory for pipeline potential measurements. When reference electrode-to-reference electrode potential measurements are made in the field, it is necessary that electrodes with matching potentials be used.

Appendix B: Net Protective Current

B1 NACE Standard RP0169,¹ Paragraph 6.2.2.2.1, states that measuring the net protective current from the electrolyte to the pipe surface by an earth current technique at predetermined current discharge points may be sufficient on bare or ineffectively coated pipelines when long-line corrosion activity is of primary concern.

B1.1 This technique is a measure of the net protective current from the electrolyte onto the pipe surface and is most practicable for use on bare pipelines.

B1.2 The electrolyte current measurements often are not meaningful in multiple pipe rights-of-way, high-resistivity electrolyte, deeply buried pipe, large-diameter pipe, stray current areas, and pipe that is not electrically isolated from other underground structures. Using this technique does not confirm elimination of local corrosion cell action.

B2 Measurement Techniques for Net Protective Current

B2.1 The principal anodic areas along the pipeline should be located. Sufficient cathodic protection current should be applied to cause a net protective current from the electrolyte to the pipe surface. The pipe-to-electrolyte potential measurements for these techniques are performed on piping that is not cathodically protected.

B2.2 The two-reference-electrode potential survey or a pipe-to-electrolyte potential survey method is used to detect the probable current discharge (anodic) areas along a pipeline.

B2.2.1 The two-reference-electrode method measures the direction of the potential gradient along the earth's surface. Measurements should be made at 3-m (10-ft) intervals directly over the centerline of the pipe. The instrument positive terminal is connected to the lead (front) reference electrode in the direction of survey travel. A suspected anodic condition is indicated by a change of the instrument polarity indication. Suspected anodic conditions and their magnitudes can be confirmed by making two-reference-electrode tests laterally to the pipeline. One reference electrode is placed over the line and the other spaced laterally the same distance as for the transverse measurements over the line. These

tests should be made on both sides of the pipe to verify that current is leaving the line.

B2.3 The pipe-to-electrolyte potential survey, when used as a tool for locating probable anodic conditions on unprotected pipe, should be conducted by making individual readings at 3-m (10-ft) intervals along the route of the pipe. Probable anodic conditions are indicated at survey points where the most negative readings are determined. It may be desirable to confirm these suspected anodic conditions by making the two-reference-electrode test lateral to the pipe as described for the two-reference-electrode method.

B3 Two-Reference-Electrode Surface Survey

B3.1 Two-reference-electrode surface measurements consist of measuring the potential difference between two matched CSEs in contact with the earth. This type of test, when made directly over the route of the pipe, is useful in locating suspected anodic conditions on the pipe. The two-reference-electrode survey is particularly suited for bare pipe surveys to locate anodic areas for applying a "hot spot" type of protection. The technique is not usually used on coated pipe.

B3.2 For this survey technique to be effective, special attention shall be given to the reference electrodes used. Because potential values to be measured can be expected to be as low as 1 mV, the reference electrodes shall be balanced to within 3 mV of each other. The potential difference between reference electrodes can be measured by:

- (a) Placing about 2.5 cm (1 in.) depth of tap water in a small plastic or glass container;
- (b) Placing the two reference electrodes in the water; and
- (c) Measuring the potential difference between them.

B3.2.1 If the potential difference between the two reference electrodes is not satisfactory, they can be corrected by servicing both reference electrodes. This may be accomplished by thoroughly cleaning the inside of the plastic body, rinsing it with distilled water, soaking the porous plug in distilled water or simply replacing the old plug with a new one, cleaning the copper rod

inside the reference electrode, and replacing the solution with new, clean saturated copper sulfate solution. If the first cleaning does not achieve the desired results, the process should be repeated. The copper rod should never be cleaned with emery cloth or any other material with metallic abrasive. Only nonmetallic sandpaper should be used.

NOTE: Reference electrode potential values may change during the survey. Therefore, it is desirable to check reference electrodes periodically for balance and to have matched or balanced spares available for replacement if needed.

B3.3 A voltmeter with sufficiently high input impedance, at least 10 megaohms, and sufficiently low ranges should be used to make the two-reference-electrode surface survey. Measured values are usually less than 50 mV. The required equipment for this survey includes an appropriate voltmeter, two balanced CSEs, and related test leads. The front reference electrode in the direction of travel shall be connected to the positive terminal of the instrument. (See Figure B1.)

B3.4 Careful placement of reference electrodes is essential when using the two-reference-electrode surface survey. Minor measurement errors due to incorrect placement of the reference electrodes can result in misinterpretation of the data. Before the survey is conducted, the pipe should be accurately located and marked, using a dependable locating device. Special care shall be exercised in situations in which multiple pipelines are on the same right-of-way.

B3.5 Reference electrode spacing should be uniform. A spacing of 3 m (10 ft) is acceptable. When a ground gradient reversal (anodic condition) has been located, the spacing may be reduced by one half and the area reexamined to locate the anodic area more closely.

B3.6 The survey is made by placing two reference electrodes in the earth at the selected spacing directly over the pipeline. The front test lead in the direction of travel is connected to the positive terminal of the instrument. Because the voltage values between the reference electrodes are normally low, it is desirable that the reference electrode contact with the earth be free of leaves, grass, rocks, and other debris.

B3.7 Results of the measurement are recorded on an appropriate form. Special attention shall be given to recording the polarity of each voltage measurement correctly. With the reference electrodes placed and the instrument connected as described, a possibly anodic condition is indicated when a polarity change occurs. (When the polarity of the measured value changes again, a possibly cathodic condition is indicated.) (See Figure B1.)

B3.8 The severity and extent of an anodic condition may be further determined by making two-reference-electrode surface measurements lateral to the direction of the pipe. This is accomplished by relocating the rear reference electrode to the side of the pipe. A positive value measured from this side reference electrode indicates current flowing from the pipe into the electrolyte, which is an anodic condition. A negative value measured from this side reference electrode toward the reference electrode over the pipe indicates current flowing from the electrolyte toward the pipe, which is a cathodic condition. Measurements should be taken on both sides of the pipe. Enough measurements along the pipe and on both sides of the pipe should be taken to define the limits of the anodic condition.

B3.9 The presence of a galvanic anode connected to the pipe affects two-reference-electrode surface measurements and generally appears as an anodic condition. Close observation of measured values quite often suggests the presence of galvanic anodes. As an anode is approached, its presence is usually indicated by earth gradients that are somewhat higher than normal for the area being surveyed. The two-reference-electrode lateral test may provide higher measured values on the side of the pipe where the anode is buried and lower values on the side of the pipe opposite the anode. Service taps, side connections, other components of the pipe (such as mechanical couplings or screw collars with a higher metallic resistance than the pipe), or other close buried metallic structures may provide measured values that indicate an anodic condition. The lateral test is useful to evaluate the data. Any situation not determined to be caused by some other factor shall be considered as an anodic condition. Adequate marking of anodic conditions is necessary so they can be located for future attention.

B3.10 Soil resistivity tests should be made at anodic areas discovered by using the two-reference-electrode surface survey. These tests are helpful in evaluating the severity of ongoing corrosion, anode current, and anode life.

B3.11 The two-reference-electrode surface potential survey data may be used to generate a pipe-to-electrolyte potential gradient curve using closely spaced measurements. This curve appears as any other pipe-to-electrolyte potential curve and is generated by the following procedure:

B3.11.1 The pipe-to-electrolyte potential is measured at a test point, such as a test station. This value is recorded and becomes the reference value to which all other two-reference-electrode measurements are referenced.

B3.11.2 The reference electrode is left in the same location and is connected to the negative terminal of the voltmeter. A second reference electrode is

placed over the pipe centerline in clean, moist earth a selected distance from the first reference electrode and is connected to the positive side of the instrument.

B3.11.3 The potential between the two reference electrodes is then measured and recorded. Special attention shall be given to the polarity of the measurement between the two reference electrodes.

B3.11.4 The measured value is then algebraically added to the pipe-to-electrolyte potential measured in the first step of this procedure. The sum obtained from the algebraic addition is the pipe-to-electrolyte potential at the location of the second reference electrode.

B3.11.5 The rear reference electrode (connected to the instrument negative terminal) is moved forward and placed in the same spot previously occupied by the front reference electrode.

B3.11.6 The front reference electrode is moved ahead over the line to the previously selected distance.

B3.11.7 The potential between the two reference electrodes is again measured with special attention to reference electrode polarity. This value is algebraically added to the calculated value for the previous test. This calculated pipe-to-electrolyte potential is the pipe-to-electrolyte potential at the location of the front reference electrode.

B3.11.8 This process is repeated until the next test station is met. At this time the last calculated pipe-to-electrolyte potential is compared with the pipe-to-electrolyte potential measured using the test station. If the survey is carefully performed, upon comparison these two values should be nearly identical.

B3.11.9 These potential data can then be plotted as a typical pipe-to-electrolyte potential curve.

B3.12 Errors in observing instrument polarities, incorrect algebraic calculations, unbalanced reference electrodes, and poor earth/reference electrode contacts cause the calculated values to be incorrect.

B3.13 To use the data collected effectively, a form having a suitable format should be developed. The specific needs of each user should be considered when a data form is being developed. The form should have space for each measured numerical value, the polarity of each value, calculated values, and comments. It is also useful to provide space for a sketch of the area surveyed.

B4 Data Interpretation:

B4.1 Interpretation of survey data is complex but should consider the following:

- (a) Polarity change of a measured value;
- (b) Magnitude of the value measured;
- (c) Magnitude of the lateral two-reference-electrode value;
- (d) Soil resistivity;
- (e) Unknown pipe resistances;
- (f) Physical location of the pipe with respect to other structures; and
- (g) Known corrosion leak history.

B5 Pipe-to-Electrolyte Potential Survey

B5.1 Pipe-to-electrolyte potential measurements measure the potential difference between a CSE in contact with the earth and a connection to the pipeline. When taken and recorded at measurement intervals of 3 m (10 ft) directly over a pipeline, these measurements are useful in locating suspected anodic conditions of an unprotected pipeline. The interval of measurement may be shortened when anodic conditions are indicated or other unusual conditions occur (see Figures B2a and B2b).

B5.2 Individual users may find it appropriate to modify the above suggested spacing based on the following conditions.

- (a) Pipeline length;
- (b) Availability of test leads to the pipe;
- (c) Terrain characteristics;
- (d) Accessibility;
- (e) Presence of foreign pipelines and cathodic protection systems;
- (f) Coating condition or lack of coating;
- (g) Corrosion history of the pipeline;
- (h) Results of previous surveys; and
- (i) Pipe depth.

B5.3 The survey consists of measuring and recording voltages along an unprotected pipeline at specific intervals as shown in Figures B2a and B2b. To interpret the survey data correctly and to ensure meaningful results, the pipeline must be electrically continuous, or the location of insulating or high-resistance joints must be known. The "peaks," or areas of highest negative potential, usually indicate anodic conditions. Pipe-to-electrolyte potential measurements should be plotted or tabulated (see Figure B2c).

B5.4 The presence of an unknown galvanic anode affects measurements, causing a location to appear to be an anodic condition. If records or measurements do not indicate that a galvanic anode has been installed, all "peaks" shall be considered as anodic conditions. If records regarding galvanic anodes in the area are not available or are believed to be inaccurate, a few additional measurements can help to determine the source of the peaks. Pipe-to-electrolyte (or electrode-to-electrode) potential measurements should be made

in 0.3-m (1-ft) increments for about 1.5 to 3.0 m (5 to 10 ft) laterally to the pipe and through the "peak." The maximum potential will occur a few feet to the side of the pipe if the peak is due to a galvanic anode. Moreover, if the pipe location is known with certainty and a galvanic anode is present, the potentials will be a minimum over or to the side of the pipe opposite where the maximum occurs. The closer the transverse measurements are to the anode, the more the location of the minimum will be shifted away from the side of the pipe opposite the location of the maximum.

B5.5 Stray current flowing to a pipe from sources such as foreign rectifiers and electrified railroads cause the pipe at that location to have more-negative potential and may be misinterpreted as an anodic condition. Stray current discharging from a pipe can cause a less-negative potential and be misinterpreted as a cathodic condition.

B6 Cathodic Protection Using the Net Protective Current Technique

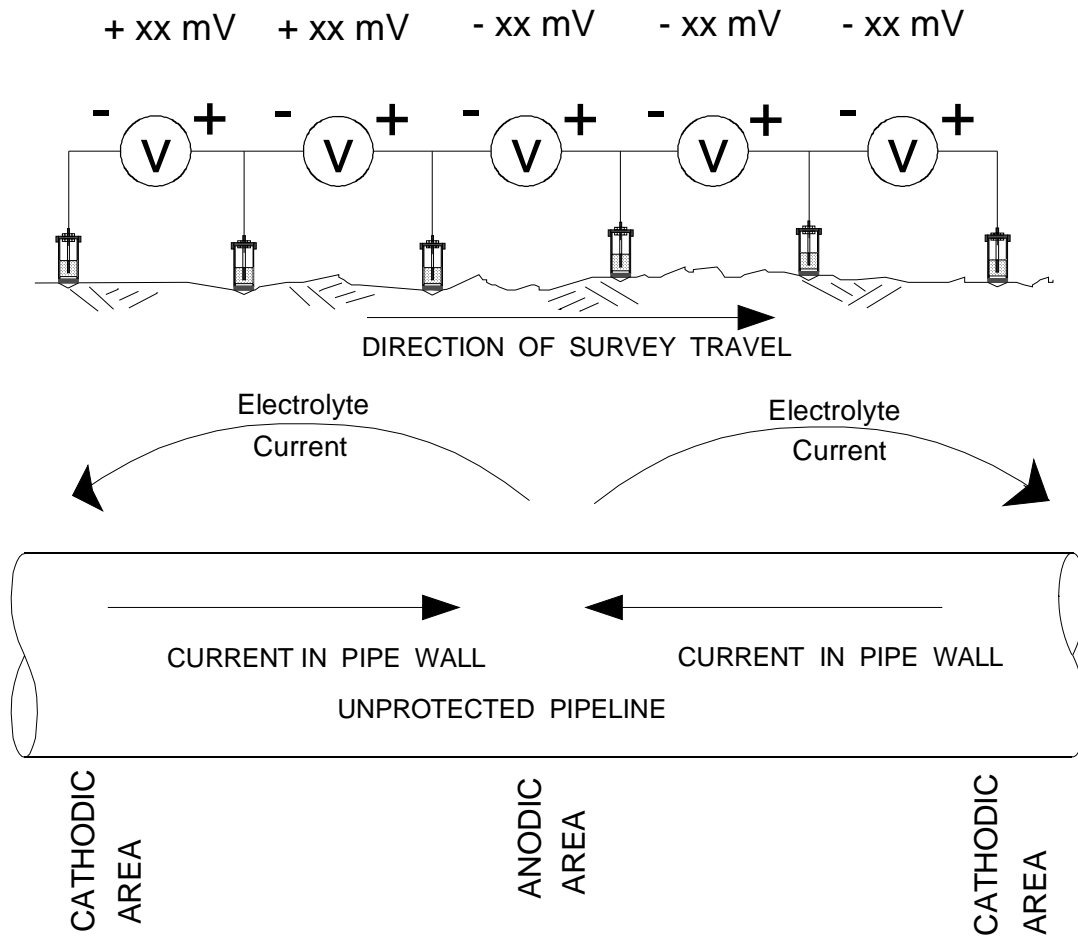
B6.1 Cathodic protection should be applied to the anodic area(s).

B6.2 It is necessary to wait until polarization has stabilized before making a detailed evaluation of the net current protective level. Polarization of bare pipe may require a relatively long time ranging up to several months.

B6.3 When an impressed current source is used, the side drain potential (potential gradient lateral to the pipe longitudinal direction) should be measured at the predetermined anodic condition with the protective current applied. Relative to the reading directly over the pipe, a higher (more-negative) reading with the reference electrode lateral to the pipe indicates that current is being conducted to the pipe at this point. The amount of current flow indicated by this method may not be enough to control small local corrosion cells.

B6.4 Galvanic anodes are usually installed at or near the location of the anodic areas. Caution shall be used when interpreting the results of pipe-to-electrolyte potential measurements made close to an anode.

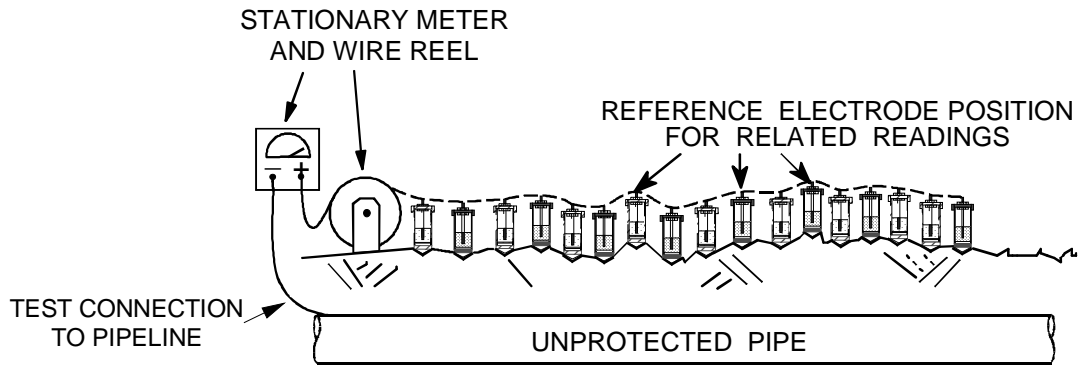
B6.5 Monitoring of cathodic protection can be simplified by establishing test points and recording the pipe-to-electrolyte potential exhibited when the side drain measurements indicate a net current flow to the pipe. These potentials may then be used to monitor the level of cathodic protection.



NOTE: Actual readings are usually 50 mV or less.

As the anodic condition in the center of the figure is passed (traveling left to right), the indicated polarity switches from positive to negative. This polarity reversal indicates an anodic condition.

FIGURE B1
Surface Potential Survey



Significant errors in the potential measurements can occur when surveys are undertaken as shown if there is a break in the lead wire insulation or if leakage occurs through the insulation.

Figure B2a
Reference Electrode Intervals for Potential Survey Using Stationary Meter and Wire Reel.

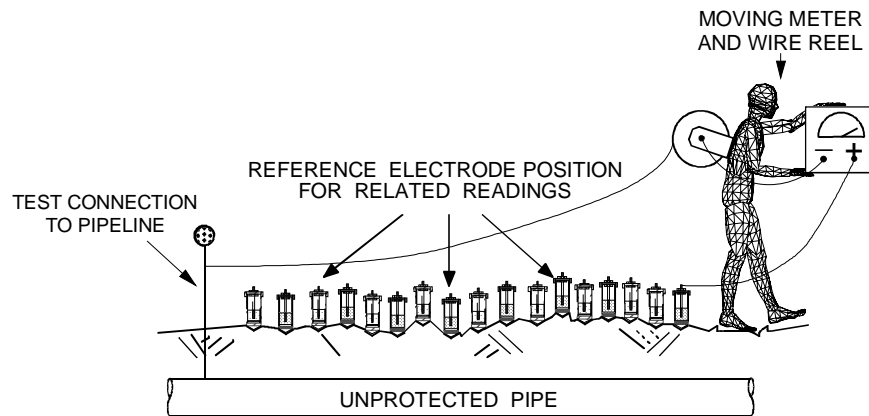


Figure B2b
Reference Electrode Intervals for Potential Survey Using Moving Meter and Wire Reel.

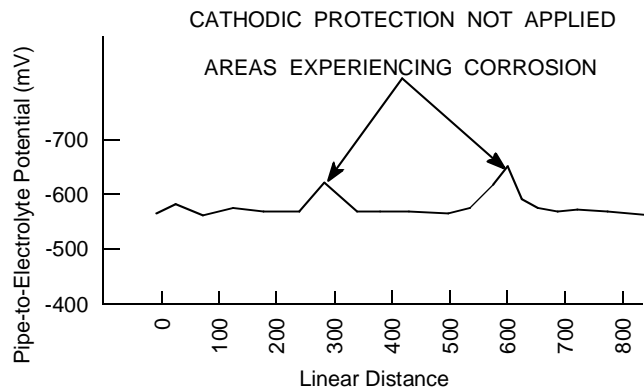


Figure B2c
Variation of Pipe-to-Electrolyte Potential with Survey Distance

FIGURE B2 Pipe-to-Electrolyte Potential Survey of a Noncathodically Protected Pipeline

Appendix C: Using Coupons to Determine Adequacy of Cathodic Protection

C1 Coupons have been used judiciously, particularly when accompanied by other engineering tools and data, to evaluate whether cathodic protection at a test site complies with a given criterion. See NACE Publication 35201⁴ for more information on coupon use. The following test procedures are suggested as guides.

C2 Cathodic Protection Coupon Test Method 1—for Negative 850 mV Polarized Pipe-to-Electrolyte Potential of Steel and Cast Iron Piping

C2.1 Scope

This method uses a cathodic protection coupon to assess the adequacy of cathodic protection on a steel or cast iron pipeline according to the criterion stated in NACE Standard RP0169,¹ Paragraph 6.2.2.1.2:

A negative polarized potential of at least 850 mV relative to a saturated copper/copper sulfate reference electrode (CSE).

C2.2 General

C2.2.1 This method uses a coupon to assess the adequacy of cathodic protection applied to a selected test site. A cathodic protection coupon is a metal sample representing the pipeline at the test site and used for cathodic protection testing. The coupon should be:

- (a) Nominally of the same metal and surface condition as the pipe;
- (b) Small to avoid excessive current drain on the cathodic protection system;
- (c) Placed at pipe depth in the same backfill as the pipe;
- (d) Prepared with all mill scale and foreign materials removed from the surface; and
- (e) Placed at a known location of an ineffective coating when the line is coated.

C2.2.2 A coupon has an insulated test lead brought above ground and, during normal operations, connected to a pipeline test lead. The coupon receives cathodic protection current and represents the pipeline at the test site. For testing purposes, this connection is opened, and the polarized potential of the coupon is measured. The time the connection is open to measure the coupon's "off" potential should be minimized to avoid significant depolarization of the coupon. The "off" period is typically less than 3 seconds. When possible, coupon current direction and magnitude should be verified, using a current clip gauge or resistor permanently placed in series with the coupon lead. Measurements showing discharge

of current from the coupon should be reason to question the validity of using a coupon at the test site.

C2.2.3 The significance of voltage drops due to currents from other sources may not be a problem when a coupon is used to represent the pipeline. The coupon's small size may reduce the effect of these voltage drops. The magnitude of these voltage drops can be quantified by interrupting cathodic protection current sources while the coupon is disconnected and noting whether there is a shift in the coupon-to-electrolyte potential.

C2.3 Comparison with Other Methods

C2.3.1 Advantages

- (a) Can provide a polarized coupon-to-electrolyte potential, free of voltage drop, with a minimum of specialized equipment, personnel, and vehicles; and
- (b) Can provide a more comprehensive evaluation of the polarization at the test site than conventional pipe-to-electrolyte potential measurements that may be influenced by the location, size, and number of coating holidays when the pipeline is coated.

C2.3.2 Disadvantage—Can have high initial costs to install coupons, especially for existing pipelines.

C2.4 Basic Test Equipment

C2.4.1 Voltmeter with adequate input impedance. Commonly used digital instruments have a nominal impedance of 10 megaohms. An analog instrument with an internal resistance of 100,000 ohms per volt may be adequate in certain circumstances in which the circuit resistance is low. A potentiometer circuit may be necessary in other instances.

C2.4.2 Two color-coded meter leads with clips for connection to the coupon and reference electrode.

C2.4.3 Reference electrode

C2.4.3.1 CSE

C2.4.3.2 Other standard reference electrodes may be substituted for the CSE. These reference electrodes are described in Appendix A, Paragraph A2.

C2.5 Procedure

C2.5.1 Before the test, verify that:

- (a) Cathodic protection equipment has been installed and is operating properly; and
- (b) Coupon is in place and connected to a pipeline test lead.

Time should be allowed for the pipeline and coupon potentials to reach polarized values.

C2.5.2 Determine the location of the site to be tested. Selection of a site may be based on:

- (a) Location accessible for future monitoring;
- (b) Other protection systems, structures, and anodes that may influence the pipe-to-electrolyte and coupon-to-electrolyte potentials;
- (c) Electrical midpoints between protection devices;
- (d) Known location of an ineffective coating when the line is coated; and
- (e) Location of a known or suspected corrosive environment.

C2.5.3 Make electrical contact between the reference electrode and the electrolyte at the test site as close to the coupon as is practicable.

C2.5.4 Connect the voltmeter to the coupon test lead and reference electrode as described in Paragraph 5.6.

C2.5.5 Measure and record the pipeline and coupon "on" potentials.

C2.5.6 Momentarily disconnect the coupon test lead from the pipeline test lead and immediately measure and record the coupon-to-electrolyte "off" potential and its polarity with respect to the reference electrode. This should be performed quickly to avoid depolarization of the coupon.

C2.5.7 Reconnect the coupon test lead to the pipeline test lead for normal operations.

C2.6 Evaluation of Data

Cathodic protection may be judged adequate at the test site if the polarized coupon-to-electrolyte potential is negative 850 mV, or more negative, with respect to a CSE. The polarized potential of the coupon depends on the coupon surface condition, the soil in which the coupon is placed, its level of polarization, and its time polarized. Therefore, the polarized potential of the coupon may not be the same as that of the pipe and may not accurately reflect the polarization on the pipe at the coupon location. It must also be understood that the polarization measured on the pipeline is a "resultant" of the variations of polarization on the pipe at the test site. The causes of these variations include the pipe surface condition, soil strata variations, oxygen differentials, and length of time the pipe has been

polarized. Making precise comparisons may not be possible.

C2.7 Monitoring

When the polarized coupon-to-electrolyte potential has been determined to equal or to exceed a negative 850 mV, the pipeline "on" potential may be used for monitoring unless significant environmental, structural, coating integrity, or cathodic protection system parameters have changed.

C3 Cathodic Protection Coupon Test Method 2—for 100 mV Cathodic Polarization of Steel, Cast Iron, Aluminum, and Copper Piping

C3.1 Scope

This method uses cathodic protection coupon polarization decay to assess the adequacy of cathodic protection on a steel, cast iron, aluminum, or copper pipeline according to the criteria stated in NACE Standard RP0169,¹ Paragraphs 6.2.2.1.3, 6.2.3.1, or 6.2.4.1 (depending on the pipe metal). The paragraph below states Paragraph 6.2.2.1.3:

The following criterion shall apply: A minimum of 100 mV of cathodic polarization between the structure surface and a stable reference electrode contacting the electrolyte. The formation or decay of polarization can be measured to satisfy this criterion.

C3.2 General

Ferrous, aluminum, and copper pipelines may be adequately cathodically protected when applying cathodic protection causes a polarization change of 100 mV or more with respect to a reference potential.

C3.2.1 This method uses a coupon to assess the adequacy of cathodic protection applied at a test site. A cathodic protection coupon is a metal sample representing the pipeline at the test site and used for cathodic protection testing. The coupon should be:

- (a) Nominally of the same metal and surface condition as the pipe;
- (b) Small to avoid excessive current drain on the cathodic protection system;
- (c) Placed at pipe depth in the same backfill as the pipe;
- (d) Prepared with all mill scale and foreign materials removed from the surface; and
- (e) Placed at a known location of an ineffective coating when the line is coated.

C3.2.2 The significance of voltage drops due to currents from other sources may be accounted for when a coupon is used to represent the pipeline. The magnitude of these voltage drops can be

quantified by interrupting cathodic protection sources while the coupon is disconnected and noting whether there is a shift in the coupon-to-electrolyte potential.

C3.2.3 A coupon has an insulated test lead brought above ground and, during normal operations, connected to a pipeline test lead. The coupon receives cathodic protection current and represents the pipeline at the test site. For testing purposes, this connection is opened, and the polarized "off" potential of the coupon is measured. The time the connection is open to measure the coupon's "off" potential should be minimized to avoid significant depolarization of the coupon. The "off" period is typically less than 3 seconds. The coupon is then allowed to depolarize. When possible, coupon current direction and magnitude should be verified, using a current clip gauge or resistor permanently placed in series with the coupon lead. Measurements showing discharge of current from the coupon should be reason to question the validity of using a coupon at the test site.

C3.3 Comparison with Other Methods

C3.3.1 Advantages

- (a) Can measure coupon-to-electrolyte polarization decay with a minimum of specialized equipment, personnel, and vehicles;
- (b) Can provide an indication of the amount of polarization present at the test site without interrupting the cathodic protection current supplied to the pipeline;
- (c) Can provide a better indication of cathodic protection levels due to eliminating the effects of "long-line" current flow when the pipeline "off" potentials are measured.

C3.3.2 Disadvantage—Can have high initial costs to install a coupon, especially for existing pipelines.

C3.4 Basic Test Equipment

C3.4.1 Voltmeter with adequate input impedance. Commonly used digital instruments have a nominal impedance of 10 megaohms. An analog instrument with an internal resistance of 100,000 ohms per volt may be adequate in certain circumstances where the circuit resistance is low. A potentiometer circuit may be necessary in other instances.

C3.4.2 Two color-coded meter leads with clips for connection to the coupon and reference electrode.

C3.4.3 Reference electrode

C3.4.3.1 CSE.

C3.4.3.2 Other standard reference electrodes may be substituted for the CSE. These reference electrodes are described in Appendix A, Paragraph A2.

C3.5 Procedure

C3.5.1 Before the test, verify that:

- (a) Cathodic protection equipment is installed
- (b) and operating properly; and
- (c) Coupon is in place and connected to a pipeline test lead.

Time shall be allowed for the pipeline and coupon potentials to reach polarized values.

C3.5.2 Determine the location of the site to be tested. Selection of a site may be based on:

- (a) Location accessible for future monitoring;
- (b) Other protection systems, structures, and anodes that may influence the pipe-to-electrolyte and coupon-to-electrolyte potentials;
- (c) Electrical midpoints between protection devices;
- (d) Known location of an ineffective coating when the line is coated; and
- (e) Location of a known or suspected corrosive environment.

C3.5.3 Make electrical contact between the reference electrode and the electrolyte at the test site as close to the coupon as is practicable.

C3.5.3.1 Identify the location of the electrode to allow it to be returned to the same location for subsequent tests.

C3.5.4 Connect the voltmeter to the coupon test lead and reference electrode as described in Paragraph 5.6.

C3.5.5 Measure and record the pipeline and coupon "on" potentials.

C3.5.6 Disconnect the coupon test lead from the pipeline test lead and immediately measure the coupon-to-electrolyte potential.

C3.5.6.1 The coupon-to-electrolyte potential becomes the "base line value" from which polarization decay is measured.

C3.5.7 Record the coupon-to-electrolyte "off" potential and its polarity with respect to the reference electrode.

C3.5.8 Leave the coupon test lead disconnected to allow the coupon to depolarize.

C3.5.9 Measure and record the coupon-to-electrolyte potential periodically. The difference between it and the "off" potential is the amount of polarization decay. Continue to measure and record the coupon-to-electrolyte potential until it either:

- (a) Has become at least 100 mV less negative than the "off" potential; or
- (b) Has reached a stable depolarized level.

C3.5.10 Reconnect the coupon test lead to the pipeline test lead for normal operations.

C3.6 Evaluation of Data

Cathodic protection may be judged adequate at the test site when 100 mV or more of polarization decay is measured with respect to a standard reference

electrode. The depolarized potential of the coupon depends on the coupon surface condition, the soil in which the coupon is placed, its level of polarization, and its time polarized. Therefore, the depolarized potential of the coupon may not be the same as that of the pipe and may not accurately reflect the polarization on the pipe at the coupon location. It must also be understood that the polarization measured on the pipeline is a "resultant" of the variations of polarization on the pipe at the test site. These variations are caused by the pipe surface condition, soil strata variations, oxygen differentials, and time the pipe has been polarized. Making precise comparisons may not be possible.

C3.7 Monitoring

When at least 100 mV or more of polarization decay has been measured, the pipeline "on" potential at the test site may be used for monitoring unless significant environmental, structural, coating integrity, or cathodic protection system parameters have changed.

Standard Test Method

Measurement Techniques Related to Criteria for Cathodic Protection on Underground or Submerged Metallic Tank Systems

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Approved 2001-11-07
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ISBN 1-57590-137-4
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Foreword

This NACE International standard test method provides descriptions of the measurement techniques and cautionary measures most commonly used on underground tanks to determine whether a specific criterion has been complied with at a test site. This standard includes only those measurement techniques that relate to the criteria or special conditions contained in NACE Standard RP0285.¹

The measurement techniques described in this standard require that measurements be made in the field. Because these measurements are obtained under widely varying circumstances of field conditions and tank design, this standard is not as prescriptive as those NACE standard test methods that use laboratory measurements. Instead, this standard gives the user latitude to make testing decisions in the field based on the technical facts available.

This standard is intended for use by corrosion-control personnel concerned with the corrosion of buried, underground, or submerged tank systems or similar structures, including those used to contain oil, gas, and water. It was prepared by Task Group 209 (formerly Work Group T-10A-14b, a subcommittee of Task Group T-10A-14 on Test Methods and Measurement Techniques Related to Cathodic Protection Criteria). Task Group 209 is administered by Specific Technology Group (STG) 35 on Pipelines, Tanks, and Well Casings, and is sponsored by STG 05 on Cathodic/Anodic Protection. The measurement techniques provided in this standard were compiled from information submitted by committee members and others with expertise on the subject. Variations or other techniques not included may be equally effective. This standard is issued by NACE under the auspices of STG 35 on Pipelines, Tanks, and Well Casings.

In NACE standards, the terms *shall*, *must*, *should*, and *may* are used in accordance with the definitions of these terms in the *NACE Publications Style Manual*, 4th ed., Paragraph 7.4.1.9. *Shall* and *must* are used to state mandatory requirements. The term *should* is used to state something good and is recommended but is not mandatory. The term *may* is used to state something considered optional.

**NACE International
Standard
Test Method**

**Measurement Techniques Related to Criteria
for Cathodic Protection on Underground
or Submerged Metallic Tank Systems**

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Section 1: General

1.1 This standard provides procedures to test compliance with the cathodic protection (CP) criteria presented in NACE Standard RP0285¹ on buried or submerged steel tank systems, including galvanized steel components. Included are instrumentation and general measurement guidelines, procedures for three commonly used testing methods, recommendations on taking voltage drops into consideration and preventing incorrect data from being collected and used, and procedures for testing for electrical continuity between tanks and other metallic equipment. A method of testing cathodic protection using coupons is described in Appendix A.

1.2 The provisions of this test method shall be applied by personnel who have acquired, by education and related

practical experience, knowledge of the principles of cathodic protection of buried and submerged metallic tank systems.

1.3 Sometimes a given test technique is ineffective or only partially effective. Conditions that may cause this to occur include elevated temperatures, disbonded dielectric or thermally insulating coatings, shielding, bacterial attack, and unusual contaminants in the electrolyte.

1.4 Deviation from this test method may be warranted in specific situations if corrosion-control personnel can demonstrate that adequate cathodic protection has been achieved.

Section 2: Definitions⁽¹⁾

Anode: The electrode of an electrochemical cell at which oxidation occurs. Electrons flow away from the anode in the external circuit. Corrosion usually occurs and metal ions enter the solution at the anode.

Cable: A bound or sheathed group of insulated conductors.

Cathode: The electrode of an electrochemical cell at which reduction is the principal reaction. Electrons flow toward the cathode in the external circuit.

Cathodic Disbondment: The destruction of adhesion between a coating and the coated surface caused by products of a cathodic reaction.

Cathodic Polarization: The change of electrode potential in the active (negative) direction caused by current across the electrode/electrolyte interface. See also *Polarization*.

Cathodic Protection: A technique to reduce the corrosion of a metal surface by making that surface the cathode of an electrochemical cell.

Cathodic Protection Coupon: A metal sample representing the tank at the test site, used for cathodic protection testing, and having a chemical composition approximating that of the tank. The coupon size should be small to avoid excessive current drain on the cathodic protection system.

Coating: A liquid, liquefiable, or mastic composition that, after application to a surface, is converted into a solid protective, decorative, or functional adherent film.

Conductor: A bare or insulated material suitable for carrying electric current.

Contact Resistance: The resistance in the measurement circuit present in the interface between a reference electrode and an electrolyte.

Corrosion: The deterioration of a material, usually a metal, that results from a reaction with its environment.

Corrosion Potential (E_{corr}): The potential of a corroding surface in an electrolyte relative to a reference electrode under open-circuit conditions (also known as rest potential, open-circuit potential, or freely corroding potential).

Criterion: A standard for assessment of the effectiveness of a cathodic protection system.

Current Density: The current to or from a unit area of an electrode surface.

Electrical Isolation: The condition of being electrically separated from other metallic structures or the environment.

⁽¹⁾ Definitions in this section reflect common usage among practicing corrosion-control personnel and apply specifically to how terms are used in this standard. As much as possible, these definitions are in accord with those in the "NACE International Glossary of Corrosion-Related Terms."

Electrode: A conductor used to establish contact with an electrolyte and through which current is transferred to or from an electrolyte.

Electrode Potential: The potential of an electrode in an electrolyte as measured against a reference electrode. (The electrode potential does not include any resistance losses in potential in either the electrolyte or the external circuit. It represents the reversible work to move a unit charge from the electrode surface through the electrolyte to the reference electrode.)

Electrolyte: A chemical substance containing ions that migrate in an electric field. (For the purpose of this test method, electrolyte refers to the soil or liquid, including contained moisture and other chemicals, next to and in contact with a buried or submerged metallic tank system.)

Foreign Structure: Any metallic structure that is not intended as part of a system under cathodic protection.

Free Corrosion Potential: See *Corrosion Potential*.

Galvanic Anode: A metal that provides sacrificial protection to another metal that is more noble when electrically coupled in an electrolyte. This type of anode is the electron source in one type of cathodic protection.

Groundbed: One or more anodes installed below the earth's surface for the purpose of supplying cathodic protection.

Holiday: A discontinuity in a protective coating that exposes unprotected surface to the environment.

Impressed Current: An electric current supplied by a device employing a power source that is external to the electrode system. (An example is direct current for cathodic protection.)

"Instant-Off" Potential: A measurement of a tank-to-electrolyte potential made without perceptible delay following the interruption of cathodic protection.

Interference: Any electrical disturbance on a metallic structure as a result of stray current.

Isolation: See *Electrical Isolation*.

"Off" or "On": A condition whereby cathodic protection current is either turned off or on.

Polarization: The change from the open-circuit potential as a result of current across the electrode/electrolyte interface.

Polarized Potential: The potential across the structure/electrolyte interface that is the sum of the corrosion potential and the cathodic polarization.

Potential Gradient: A change in the potential with respect to distance, expressed in mV per unit of distance.

Potentiometer: A device for the measurement of an electromotive force by comparison with a known potential difference.

Protection Potential: A measured potential meeting the requirements of a cathodic protection criterion.

Reference Electrode: An electrode whose open-circuit potential is constant under similar conditions of measurement, which is used for measuring the relative potentials of other electrodes.

Remote Earth: A location of the earth far enough from the affected structure that the soil potential gradients associated with currents entering the earth from the affected structure are insignificant.

Resistance to Electrolyte: The resistance of a structure to the surrounding electrolyte.

Reverse-Current Switch: A device that prevents the reversal of direct current through a metallic conductor.

Shielding: Preventing or diverting the cathodic protection current from its intended path to the structure to be protected.

Sound Engineering Practices: Reasoning exhibited or based on thorough knowledge and experience, logically valid, and having technically correct premises that demonstrate good judgment or sense in the application of science.

Stray Current: Current through paths other than the intended circuit.

Structure: Tanks, piping, and associated equipment that may/may not be under the influence of a cathodic protection system.

Tank System: The equipment and facility constructed, maintained, or used for underground storage of products including tanks, piping, pumps, and appurtenances associated with filling, storage, and dispensing of the stored products.

Tank-to-Electrolyte Potential: The potential difference between the tank metallic surface and the electrolyte that is measured with reference to an electrode in contact with the electrolyte. This measurement is commonly called tank-to-soil (T/S).

Tank-to-Soil Potential: See *Tank-to-Electrolyte Potential*.

Telluric Current: A current flowing through the ground due to natural causes, such as the earth's magnetic field or auroral activity.

Test Lead: A wire or cable attached to a structure for connection of a test instrument to make cathodic protection potential or current measurements.

UST System: Underground Storage Tank System. See *Tank System*.

Voltage: An electromotive force or a difference in electrode potentials expressed in V.

Voltage Drop: The voltage across a resistance according to Ohm's law.

Wire: A slender rod or filament of drawn metal. In practice, the term is also used for smaller-gauge conductors (size 6 mm² [0.009 in.²] [No. 10 American Wire Gauge {AWG}] or smaller).

Section 3: Safety Considerations

3.1 Personnel who install, adjust, repair, remove, or test impressed current protection equipment shall be knowledgeable and qualified in electrical safety precautions before work is begun. The following procedures shall be implemented when electrical measurements are made:

3.1.1 Use properly insulated test lead clips and terminals to avoid contact with an unanticipated high voltage (HV). Attach test clips one at a time using a single-hand technique for each connection.

3.1.2 Use caution when long test leads are extended near overhead high-voltage alternating current (HVAC) power lines, which can induce hazardous voltages onto the test leads. Refer to NACE Standard RP0177² for additional information about electrical safety.

3.1.3 Use caution when making tests at electrical isolation devices. Before proceeding with further tests, use appropriate voltage detection instruments or

voltmeters with insulated test leads to determine whether hazardous voltages exist.

3.1.4 Avoid testing when thunderstorms are in the area.

3.1.5 Use caution when opening manways and when stringing test leads across streets, roads, and other locations subject to vehicular and pedestrian traffic. When conditions warrant, use appropriate barricades, flagging, and/or flag persons.

3.1.6 Before entering excavations and confined spaces, inspect these areas to determine whether they are safe. Inspections may include shoring requirements for excavations and testing for hazardous atmospheres in confined spaces.

3.1.7 Observe appropriate electrical codes and applicable safety regulations.

Section 4: Instrumentation and Measurement Guidelines

4.1 Electrical measurements of cathodic protection systems require the proper selection and use of instruments. Determining tank-to-electrolyte potential, voltage drop, potential difference, and similar measurements requires instruments that have appropriate voltage ranges. The user should know the capabilities and limitations of the equipment, follow the manufacturer's instruction manual, and be skilled in the use of electrical instruments. Failure to select and use instruments correctly causes errors in cathodic protection measurements.

4.1.1 Analog instruments are usually specified in terms of input resistance or internal resistance. This is usually expressed as ohms/volt (Ω/V) of full-scale meter deflection.

4.1.2 Digital instruments are usually specified in terms of input impedance expressed as megohms.

4.2 Factors that may influence instrument selection for field testing include:

- (a) Input impedance (digital instruments);
- (b) Input resistance or internal resistance (analog instruments);
- (c) Sensitivity;
- (d) Conversion speed of analog-to-digital converters used in digital or data-logging instruments;
- (e) Accuracy;
- (f) Instrument resolution;
- (g) Ruggedness;
- (h) Alternating current (AC) and radio frequency (RF) signal rejection; and
- (i) Temperature and/or climate limitations.

4.2.1 Digital instruments are capable of measuring and processing voltage readings many times per second. Evaluation of the input waveform processing may be required if an instrument does not give consistent results.

4.2.2 Measurement of tank-to-electrolyte potentials on tanks or systems affected by dynamic stray currents

may require the use of recording or analog instruments to improve measurement accuracy. Dynamic stray currents include those from electric railway systems and mining equipment.

4.3 Instrument Effects on Voltage Measurements

4.3.1 To measure tank-to-electrolyte potentials accurately, a digital voltmeter must have a high input impedance (high internal resistance, for an analog instrument) compared with the total resistance of the measurement circuit.

4.3.1.1 A digital meter used to measure tank-to-electrolyte potential should have an input impedance of 10 megohms or more. However, an instrument with a lower input impedance may produce valid data if circuit contact errors are considered. One means of making accurate measurements is to use a potentiometer circuit in an analog meter.

4.3.1.2 A voltmeter measures the potential across its terminals within its design accuracy. However, current flowing through the instrument creates measurement errors due to voltage drops that occur in all resistive components of a measurement circuit.

4.3.2 Some analog-to-digital converters used in digital and data-logging instruments operate so fast that the instrument may indicate only a portion of the input waveform and thus provide incorrect voltage indications.

4.3.3 Parallax errors on an analog instrument can be minimized by viewing the needle perpendicular to the

face of the instrument on the centerline projected from the needle point.

4.3.4 The effect of measurement circuit resistance errors may be evaluated using an instrument with two or more input impedances (internal resistance, for analog instruments) and comparing the values measured using different input impedances. If the measured values are essentially identical, measurement circuit resistance errors are negligible. Corrections must be made if measured values are not essentially identical. Digital voltmeters that have a single input impedance cannot be used for indicating measurement circuit resistance errors. Alternative measurements can be made with a potentiometer or by using two digital voltmeters with different input impedance values.

4.3.5 Specialized equipment that uses various techniques to measure the impressed current waveform and calculate a tank-to-electrolyte potential free of voltage drop is available. This equipment may minimize problems resulting from spiking effects, drifting of interrupters, and current from other direct current (DC) sources.

4.4 Instrument Accuracy

4.4.1 Instruments must be scheduled for periodic calibration to a certified standard. Instruments shall be checked for accuracy before use by comparing readings to a standard voltage cell, to another acceptable voltage source, or to another appropriate instrument that has been appropriately calibrated for accuracy.

Section 5: Tank-to-Electrolyte Potential Measurements

5.1 Voltmeters used to measure AC voltage, DC voltage, or other electrical functions usually have one terminal designated "Common" (COM). This terminal is either black in color or has a negative symbol (-). The positive terminal is either red in color or has a positive symbol (+).

5.1.1 The positive and negative symbols in the voltmeter display indicate the direction of the current flow through the instrument. For example, a positive value in the voltmeter display indicates current flowing from the positive terminal through the voltmeter to the negative terminal (Figure 1a).

5.1.2 Usually, one voltmeter test lead is black and the other is red. The black test lead is connected to the negative terminal of the voltmeter, and the red lead is connected to the positive terminal.

5.2 The usual technique to determine the DC voltage across battery terminals, across a tank-to-electrolyte interface, or from another DC system is to connect the black test lead to the negative side of the circuit and the red test lead to the positive side of the circuit. When connected in this manner, an analog instrument needle moves in an upscale (clockwise) direction indicating a positive value with relation to the negative terminal. A digital instrument connected in the same manner displays a digital value, preceded by a positive symbol or no symbol at all. In each situation the measured voltage is positive with respect to the instrument's negative terminal. (See instrument connections in Figure 1a.)

5.3 Voltage measurements should be made using the lowest range on the instrument. For an analog instrument, the voltage measurement is more accurate when it is measured in the upper two-thirds of a range selected for a particular instrument.

5.4 The voltage difference between a reference electrode and a metal tank can be measured with a voltmeter. The reference electrode potential is normally positive with respect to the ferrous tank; conversely, the ferrous tank is negative with respect to the reference electrode.

5.5 A tank-to-electrolyte potential is measured using a DC voltmeter having an appropriate input impedance (or internal resistance, for an analog instrument), voltage range(s), test leads, and a stable reference electrode, such as a saturated copper/copper sulfate electrode (CSE), silver/silver chloride (Ag/AgCl) electrode, or saturated potassium chloride (KCl) calomel reference electrode. The reference electrode can be portable or one designed for permanent installation.

5.5.1 CSEs are usually used for measurements if the electrolyte is soil or fresh water; they are sometimes used for measurements in salt water. If a CSE is used in a high-chloride environment, the stability (lack of contamination) of the CSE must be determined before the readings may be considered valid.

5.5.2 The Ag/AgCl reference electrode is usually used in seawater environments.

5.5.3 The saturated KCl calomel electrode is used mainly for laboratory work. However, more rugged, polymer-body, gel-filled, saturated KCl calomel electrodes that are suitable for field work are available, though modifications may be necessary to increase their contact area with the environment.

5.6 Meter Polarity

5.6.1 Tank-to-electrolyte potentials are often measured by connecting the negative terminal of the

measuring instrument to the tank and the positive terminal to the reference electrode placed in the electrolyte, which is in contact with the tank. With this connection, the instrument indicates that the reference electrode is positive with respect to the tank. Therefore, the tank voltage is negative with respect to the reference electrode (see Figure 1a).

5.6.2 Tank-to-electrolyte potential measurements can be made with the reference electrode connected to the instrument negative terminal and the tank connected to the positive terminal. This produces a negative voltage display on digital meters (see Figure 1b).

5.7 The tank-to-electrolyte potential measurement of a buried tank should be made with the reference electrode placed close to the tank-to-electrolyte interface. The most common practice, however, is to place the reference electrode as close to the tank as practicable, which is usually at the surface of the earth above the centerline of the tank (See Figure 1). This measurement includes a combination of the voltage drops associated with the:

- (a) Voltmeter;
- (b) Test leads;
- (c) Reference electrode;
- (d) Electrolyte;
- (e) Coating, if applied;
- (f) Tank-to-electrolyte interface; and
- (g) Electrode-to-electrolyte interface.

Note: A high-input impedance (>10 megohm) voltmeter or potentiometer voltmeter should be used to eliminate the effects of Paragraph 5.7, (a), (b), (c), (f), and (g) on the potential measurement.

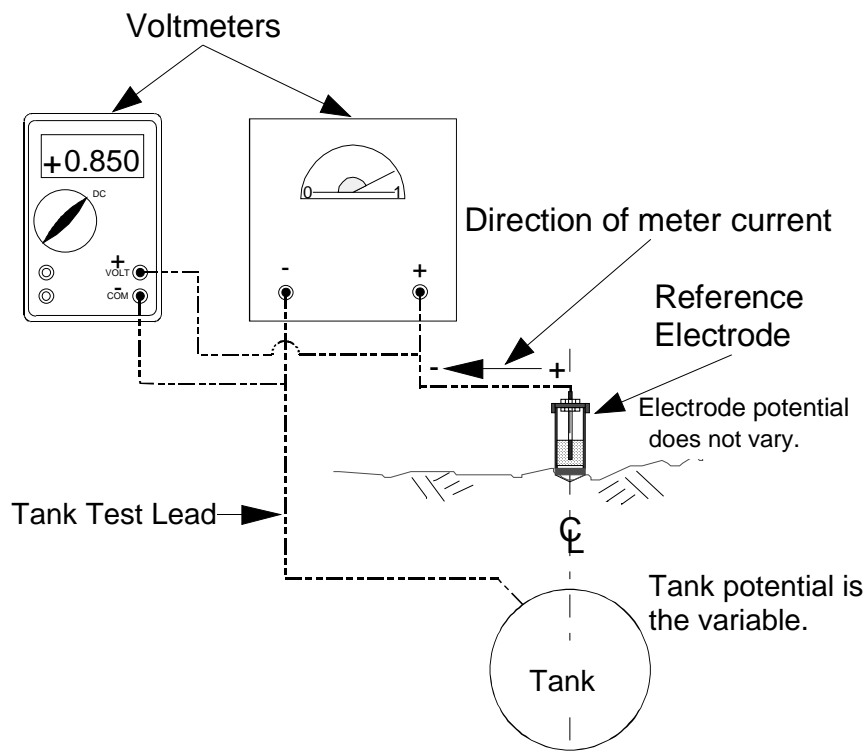


Figure 1a
Conventional Instrument Connection

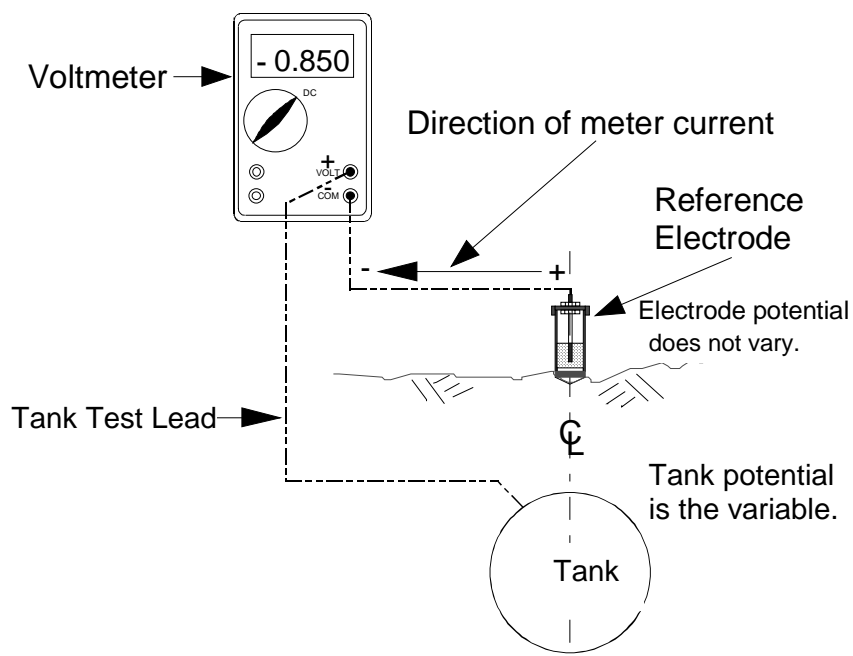


Figure 1b
Alternative Instrument Connection

Figure 1
Instrument Connections

5.8 The tank-to-electrolyte potential measurement as described above is a result of the voltage drop created by current flowing through the electrical resistances of the items listed in Paragraph 5.7. For a coated tank, coating deterioration should be considered.

5.9 All readings shall be taken with reference electrodes that are in contact with the electrolyte. Readings shall not be taken through concrete or asphalt. Soil contact may be established through at-grade openings by drilling a small hole in the concrete or asphalt, or by contacting a seam of soil between concrete and asphalt.

5.10 The following conditions should be taken into consideration when tank-to-electrolyte potential measurements are made to determine the level of cathodic protection at the test site:

- (a) Effectiveness of coatings, particularly those known or suspected to be deteriorated or damaged;
- (b) Bare sections of tank structure being protected;
- (c) Bonds to mitigate interference;
- (d) Parallel coated tanks, electrically connected and polarized to different potentials;
- (e) Shielding;
- (f) Effects of other structures on the measurements;
- (g) History of corrosion leaks and repairs;
- (h) Location and depth of anodes;
- (i) Existence of isolation devices, including high-resistance pipe connections and compression couplings;
- (j) Chemical composition of electrolytes, such as unusual corrosives, chemical spills, presence of hydrocarbons in soil, extreme soil resistivity changes, acidic waters, and contamination from sewer spills;
- (k) Possible sources of DC interference currents, such as welding equipment, foreign rectifiers, mining equipment, and electric railway or transit systems;
- (l) Contacts with other metals or structures;
- (m) Areas of construction activity during the tank history;
- (n) Underground metallic structures close to or crossing the tank;
- (o) Other appurtenances; and
- (p) Electrolyte pH.

5.11 The effect of voltage drops other than those across the tank-to-electrolyte interface shall be considered for valid interpretation of tank-to-electrolyte potential measurements made to satisfy a criterion. Measurement errors should be minimized to ensure reliable tank-to-electrolyte potential measurements.

5.12 The effect of voltage drops on a tank-to-electrolyte potential measurement can be determined by interrupting

all significant current sources before taking the potential measurement. This measurement must be taken without delay after the interruption of current to avoid loss of polarization. This measurement is referred to as an instant-off potential, and is considered to be the "polarized potential" of the tank at that location. This measurement does not account for voltage drops across the tank-to-electrolyte interface, which is part of the protection potential.

NOTE: The current interruption may cause a voltage spike. This spike shall not be recorded as the instant-off potential. The magnitude and duration of the voltage spike can vary; however, the duration is usually within 0.5 second.

5.13 The following are examples of situations in which it may not be practical to interrupt all current sources to make the instant-off potential measurement:

5.13.1 Galvanic anodes are connected directly to the tank without benefit of aboveground connections. Interruption of this kind of system requires excavation of the connections.

5.13.2 Interference from CP devices on foreign structure or electrical continuity with foreign structure.

5.13.3 Manmade sources of DC stray currents, such as other cathodic protection systems, mass transit, DC welding, or mining operations are nearby.

5.14 If voltage drops have been evaluated at a test location and the tank-to-electrolyte potential found to be satisfactory, the "on" tank-to-electrolyte potential value may be used for monitoring until significant environmental, structural, or cathodic protection system parameters change.

5.14.1 Significant environmental, structural, or cathodic protection system parameter changes may include:

- (a) Replacement or addition of tank components and systems;
- (b) Addition, relocation, or deterioration of cathodic protection systems;
- (c) Failure of electrical isolating or bonding devices;
- (d) Changes in the effectiveness of coatings;
- (e) Influence of foreign structures; and
- (f) Modification of the environment.

5.15 After a cathodic protection system is operating, time may be required for the tank to polarize. This should be taken into consideration when measuring the potential at a test site on a newly protected tank or after re-energizing a cathodic protection device.

Section 6: Causes of Measurement Errors

6.1 The following factors may contribute to faulty potential measurements:

6.1.1 Tank and instrument test leads

- (a) Broken or frayed wire strands (may not be visible inside insulation of the wire);
- (b) Damaged or defective test lead insulation that allows the conductor to contact wet vegetation, the electrolyte, or other objects;
- (c) Loose, broken, or faulty tank or instrument connections; and
- (d) Dirty or corroded connection points.

6.1.2 Reference electrode condition and placement

- (a) Contaminated reference electrode solution or rod, or solutions of insufficient quantity or saturation (only laboratory-grade chemicals and distilled water, if water is required, should be used in a reference electrode);
- (b) Reference electrode plug not sufficiently porous to provide a conductive contact to the electrolyte;
- (c) Porous plug contaminated by asphalt, oil, or other foreign materials;
- (d) High-resistance contact between reference electrode and dry or frozen soil, rock, gravel, vegetation, or paving material;
- (e) Reference electrode placed in the potential gradient of an anode without consideration of the voltage drop caused by the anode, including reference electrode placement over the top of the tank(s) protected by close anodes;
- (f) Reference electrode positioned in the potential gradient of a metallic structure other than the one whose potential is being measured without consideration of the voltage drop caused by the potential gradient of the metallic structure;
- (g) Electrolyte between tank and disbonded coating causing error due to electrode placement in electrolyte on opposite side of coating;
- (h) Defective permanently installed reference electrode;
- (i) Temperature correction not applied when needed;
- (j) Photo-sensitive measurement error (in CSE reference electrode with a clear-view window) due to light striking the electrode electrolyte solution (photovoltaic effect); and
- (k) Remote reference electrode placement in which voltage drops are not considered as part of the measurement.

6.1.3 Unknown isolating devices, such as disbonded tubing or pipe systems, can cause the tank to be electrically discontinuous between the test connection and the reference electrode location. (Section 11 provides guidance on methods of troubleshooting that identify continuity or discontinuity.)

6.1.4 Parallel paths can be inadvertently established by test personnel contacting instrument terminals or metallic parts of the test lead circuit, such as test lead clips and reference electrodes, while a potential measurement is being made.

6.1.5 The use of defective or inappropriate instruments, incorrect voltage range selection, instruments not calibrated or zeroed, or damp instruments sitting on wet earth can cause measurement errors.

6.1.6 Instruments that have an analog-to-digital converter can operate at such fast speeds that the voltage spikes produced by current interruption are indicated as the potential measurement instead of the actual "on" and "off" values.

6.1.7 The polarity of the measured value can be incorrectly observed.

6.1.8 Measurement errors can occur if the cathodic protection current-carrying conductor is used as a test lead for a tank potential measurement.

6.1.9 Electromagnetic interference or induction resulting from AC power lines or radio frequency transmitters can induce test lead and instrument errors. This condition is often indicated by a fuzzy, fluctuating, or blurred pointer movement on an analog instrument or erratic displays on digital voltmeters. For this reason, DC voltmeters must have sufficient AC rejection capability, which can be determined by referring to the manufacturer's specification.

6.1.10 The use of an internal tank connection via the fill pipe in the absence of a cathodic protection test wire when the tank has been lined can cause faulty potential measurements.

6.2 Several methods may be used to reduce contact resistance caused by the following factors:

6.2.1 Soil moisture: If the surface soil is so dry that the electrical contact of the reference electrode with the electrolyte is impaired, the soil around the electrode may be moistened with water until the contact is adequate.

6.2.2 Contact surface area: Contact resistance may be reduced by using a reference electrode with a larger contact surface area.

6.2.3 Frozen soil: Contact resistance may be reduced by removing the frozen soil to permit electrode contact with unfrozen soil.

6.2.4 Concrete or asphalt-paved areas: Contact resistance may be reduced by drilling through the

paving to permit electrode contact with the soil.

Section 7: Voltage Drops Other Than Across the Tank-to-Electrolyte Interface

7.1 Voltage drops present when tank-to-electrolyte potential measurements are made may occur in the following:

7.1.1 Measurement Circuit

7.1.1.1 The voltage drop other than across the tank-to-electrolyte interface in the measurement circuit is the sum of the individual voltage drops caused by the meter current flow through:

- (a) Instrument test lead and connection resistances;
- (b) Reference electrode internal resistance;
- (c) Reference electrode-to-electrolyte contact resistance;
- (d) Coating resistance;
- (e) Tank metallic resistance;
- (f) Electrolyte resistance;
- (g) Analog meter internal resistance; and
- (h) Digital meter internal impedance.

7.1.1.2 A measurement error occurs if the analog meter internal resistance or the digital meter internal impedance is not several orders of magnitude higher than the sum of the other resistances in the measurement circuit.

7.1.2 Electrolyte

7.1.2.1 When a tank-to-electrolyte potential is measured with cathodic protection current applied, the voltage drop in the electrolyte between the reference electrode and the tank-to-electrolyte interface shall be considered. Measurements

taken close to sacrificial or impressed current anodes can contain a large voltage drop.

7.1.2.2 Such a voltage drop can consist of, but is not limited to, the following:

- (a) A voltage drop caused by current flowing to coating holidays when the tank structure is coated; and
- (b) A voltage drop caused by large voltage gradients in the electrolyte that occur near operating anodes (sometimes called "raised earth effect").

7.1.2.3 Testing to locate anodes by moving the reference electrode along the tank may be necessary when the locations are not known.

7.1.3 Coatings

7.1.3.1 Most coatings provide protection to the tank by reducing contact between the tank surface and the environment. While the insulation provided by a coating reduces the current required for cathodic protection of a coated tank versus that required for an uncoated tank, coatings are not impervious to current flow.

7.1.3.2 Coatings resist current flow because of their relative ionic impermeability. Current flow through the resistance of the coating causes the voltage drop to be greater than that occurring when the tank is bare, under the same environmental conditions.

Section 8: Test Method 1—Negative 850-mV Tank-to-Electrolyte Potential of Steel Tanks with Cathodic Protection Applied

8.1 This section describes the most commonly used test method to satisfy the criterion stated in NACE Standard RP0285:¹

"A negative (cathodic) potential of at least 850 mV with the cathodic protection applied. This potential is measured with respect to a saturated copper/copper sulfate reference electrode contacting the electrolyte. Voltage drops other than those across the structure-to-electrolyte boundary must be considered for valid

interpretation of this voltage measurement."

8.1.1 "Consideration" is understood to mean the application of sound engineering practice in determining the significance of voltage drops by such methods as:

- (a) Measuring or calculating the voltage drop(s);
- (b) Reviewing the historical performance of the cathodic protection system;
- (c) Evaluating the physical and electrical characteristics of the tank and its environment;

- (d) Determining whether there is physical evidence of corrosion; and
- (e) Recording measurements with reference electrode placed electrically remote from the tank system, i.e., remote earth.

8.2 General

8.2.1 Test Method 1 measures the tank-to-electrolyte potential as the sum of the polarized potential and any voltage drops in the circuit. These voltage drops include those through the electrolyte and tank coating from current sources such as impressed current and galvanic anodes.

8.2.2 Cathodic protection current shall remain “on” during the measurement process. This potential is commonly referred to as the “on” potential.

8.2.3 Because voltage drops other than those across the tank-to-electrolyte interface may be included in this measurement, these drops shall be considered, as discussed in Paragraph 8.6.

8.3 Comparison with Other Methods

8.3.1 Advantages

- (a) Requires minimal equipment, and
- (b) Less time is required to make measurements.

8.3.2 Disadvantages

- (a) The potential measured includes voltage drops other than those across the tank-to-electrolyte interface;
- (b) Meeting the requirements for considering the significance of voltage drops (see Paragraph 8.6) can result in a need for additional time to assess adequacy of cathodic protection at the test site; and
- (c) Test results are difficult or impossible to analyze if stray currents are present or foreign impressed current devices are present and cannot be interrupted.

8.4 Basic Test Equipment

8.4.1 A voltmeter with adequate input impedance. Commonly used digital instruments have a nominal impedance of 10 megohms. An analog instrument with an internal resistance of 100,000 ohms per volt may be adequate in certain circumstances in which the circuit resistance is low. A potentiometer circuit may be necessary in other instances.

8.4.2 Meter leads with insulated wire and terminal connections suitable for making reliable electrical contact with the tank and reference electrode. Color-coded meter leads are suggested to avoid confusion of polarity for the measured value.

8.4.3 A CSE or other standard reference electrode may be used. Reference electrodes that may be used in place of a CSE are described in Paragraph 5.5.

8.5 The following procedure shall be followed when this test is conducted:

8.5.1 Before the test, verify that cathodic protection equipment has been installed and is operating properly. Sufficient time should be allowed for the tank potentials to reach polarized values.

8.5.2 Determine the location of reference electrode placement for potential measurements. Selection of a site may be based on:

- (a) Accessibility for future monitoring;
- (b) Other protection systems, structures, and anodes that may influence the structure-to-electrolyte potential;
- (c) Electrical midpoints between protective devices;
- (d) Known location of an ineffective coating if the tank structure is coated; and
- (e) Location of a known or suspected corrosive environment.

8.5.3 Make electrical contact between the reference electrode and the electrolyte at the test site, in a location that minimizes the voltage gradient from anodes, other structures, and coating defects (if the tank is coated).

8.5.3.1 In general, the placement of the reference electrode as close to the tank surface as possible and as far from anodes as possible minimizes many measurement errors associated with voltage drops.

8.5.3.2 Alternatively, the reference electrode may be placed at remote earth.

8.5.4 Record the location of the electrode to allow it to be returned to the same location for subsequent tests.

8.5.5 Connect the voltmeter to the tank and reference electrode as described in Paragraph 5.6.

8.5.5.1 Evaluate the effect of measurement circuit resistance on the tank-to-electrolyte potential as indicated in Paragraph 5.7.

8.5.6 Record the tank-to-electrolyte potential and its polarity with respect to the reference electrode.

8.5.7 Record a sufficient number of measurements to determine the level of cathodic protection over the entire structure.

8.6 Evaluation of Data

8.6.1 The significance of voltage drops can be considered by comparing historical levels of cathodic

protection with physical evidence from the tank to determine whether corrosion has occurred.

8.6.2 Physical evidence of corrosion is determined by evaluating items such as leak history data or buried tank inspection report data regarding locations of coating failures, localized conditions of more-corrosive electrolyte, or whether substandard cathodic protection levels have been experienced.

8.6.3 Cathodic protection shall be judged adequate at the test site if:

(a) All valid tank-to-electrolyte potential measurements are negative 850 mV, or more negative, with respect to a CSE; and

(b) The significance of voltage drops has been considered by applying the principles described in Paragraph 8.6.1 and Paragraph 8.6.2.

8.7 Monitoring

8.7.1 When the significance of a voltage drop has been considered at the test site, the measured potentials may be used for monitoring unless significant environmental, structural, coating integrity, or cathodic protection system parameters have changed.

Section 9: Test Method 2—Negative 850-mV Polarized Tank-to-Electrolyte Potential of Steel Tanks

9.1 This section describes a method that uses an interrupter(s) to eliminate the cathodic protection system voltage drop from the tank-to-electrolyte potential measurement for comparison with the criterion stated in NACE Standard RP0285.¹

“A negative polarized potential of at least 850 mV relative to a saturated copper/copper sulfate reference electrode.”

If direct-connected galvanic anodes that cannot be interrupted are present, this method is not applicable.

9.2 General

9.2.1 Interrupting the known cathodic protection current source(s) eliminates voltage drops associated with the protective currents being interrupted. However, significant voltage drops may also occur due to currents from other sources.

9.2.2 Current sources that can affect the accuracy of this test method include the following:

- (a) Unknown, inaccessible, or direct-connected galvanic anodes;
- (b) Other cathodic protection systems on associated piping or foreign structures;
- (c) Electric railway systems;
- (d) Galvanic or bimetallic cells;
- (e) DC mining equipment;
- (f) Adjacent tanks, electrically connected and polarized to different potentials; and
- (g) Unintentional connections to other structures or bonds to mitigate interference.

9.2.3 To avoid significant depolarization of the tank, the “off” period should be limited to the time necessary to make an accurate potential measurement. The “off” period is typically less than three seconds long.

9.3 Comparison with Other Methods

9.3.1 Advantages

(a) Voltage drops associated with the protective currents being interrupted are eliminated.

9.3.2 Disadvantages

- (a) Additional equipment is required;
- (b) Additional time may be required to set up equipment and to make tank-to-electrolyte potential measurements; and
- (c) Test results are difficult or impossible to analyze if stray currents are present or foreign impressed current devices are present and cannot be interrupted.

9.4 Basic Test Equipment

9.4.1 A voltmeter with adequate input impedance. Commonly used digital instruments have a nominal impedance of 10 megohms. An analog instrument with an internal resistance of 100,000 ohms per volt may be adequate in certain circumstances in which the circuit resistance is low. A potentiometer circuit may be necessary in other instances.

9.4.2 Meter leads with insulated wire and terminal connections suitable for making reliable electrical contact with the tank and reference electrode. Color-coded meter leads are suggested to avoid confusion of polarity of the measured value.

9.4.3 A CSE or other standard reference electrode may be used. Reference electrodes that may be substituted for the CSE are described in Paragraph 5.5.

9.4.4 Sufficient and adequate means to interrupt cathodic protection current sources simultaneously such as sacrificial anodes, rectifiers, and electrical bonds that are influencing the tank.

9.5 The following procedure shall be followed when this test is conducted.

9.5.1 Before the test, verify that cathodic protection equipment has been installed and is operating properly. Sufficient time should be allowed for the tank potentials to reach polarized values.

9.5.2 Install and place in operation necessary interrupter equipment in all DC current sources influencing the tank at the test site. The "off" interval should be kept as short as possible but still long enough to read a polarized tank-to-electrolyte potential after any "spike" (see Figure 2a) has collapsed.

9.5.3 Determine the location of reference electrode placement for potential measurements. Selection of a site may be based on:

- (a) Accessibility for future monitoring;
- (b) Other protection systems, structures, and anodes that may influence the structure-to-electrolyte potential;
- (c) Electrical midpoints between protective devices;
- (d) Known location of an ineffective coating if the tank structure is coated; and
- (e) Location of a known or suspected corrosive environment.

9.5.4 Make electrical contact between the reference electrode and the electrolyte at the test site, in a location that minimizes the voltage gradient from other structures, and coating defects (if the tank is coated).

9.5.4.1 Record the location of the electrode to allow it to be returned to the same location for subsequent tests.

9.5.5 Connect the voltmeter to the tank and reference electrode as described in Paragraph 5.6.

9.5.5.1 If spiking could be present, delay measurement of the tank-to-electrolyte potential to eliminate the voltage spike from the measured value. Spiking usually occurs within 0.5 second of the interruption of the cathodic protection currents. Appropriate instrumentation such as an oscilloscope or high-speed recording device may be used to verify the presence and duration of the spiking.

9.5.5.2 Evaluate the effect of measurement circuit resistance on the tank-to-electrolyte potential as indicated in Paragraph 5.7.

9.5.6 Record the tank-to-electrolyte "on" and instant-off potentials and their polarities with respect to the reference electrode.

9.5.7 Record a sufficient number of measurements to determine the level of cathodic protection over the entire structure.

9.6 Evaluation of Data

9.6.1 Cathodic protection shall be judged adequate at the test site if the polarized (instant-off) tank-to-electrolyte potential is negative 850 mV, or more negative, with respect to a CSE.

9.7 Monitoring

9.7.1 When the polarized tank-to-electrolyte potential has been determined to be equal to or greater than negative 850 mV, the tank "on" potential may be used for monitoring unless significant environmental, structural, coating integrity, or cathodic protection system parameters have changed.

Section 10: Test Method 3—100-mV Cathodic Polarization of Steel Tanks

10.1 This section describes the use of either tank polarization decay or tank polarization formation to determine whether cathodic protection is adequate at the test site according to the 100-mV criterion. Consequently, this test method consists of two mutually independent parts, Test Methods 3a and 3b, which describe the procedures for testing. Generic cathodic polarization curves for Test Methods 3a and 3b are shown in Figure 2. Figure 2 contains schematic drawings of generic polarization decay and formation. If direct-connected galvanic anodes that cannot be interrupted are present, these methods are not applicable.

10.2 Test Method 3a—Use of Tank Polarization Decay (Figure 2a)

10.2.1 This method uses tank polarization decay to assess the adequacy of cathodic protection on a steel tank according to the criterion stated in NACE Standard RP0285¹ as follows:

"The following criterion shall apply: A minimum of 100 mV of cathodic polarization. The formation or decay of polarization can be measured to satisfy this criterion."

10.2.2 General

10.2.2.1 Cathodically protected steel tanks may be adequately protected if, from the polarized

potential, the tank potential becomes less negative by 100 mV or more.

10.2.2.2 Interrupting the known cathodic protection source(s) eliminates voltage drops associated with the protective current(s) being interrupted.

10.2.2.3 Other current sources that can affect the accuracy of this test method include the following:

- (a) Unknown, inaccessible, or direct-connected galvanic anodes;
- (b) Cathodic protection systems on associated tank systems or foreign structures;
- (c) Electric railway systems;
- (d) Galvanic, or bimetallic, cells;
- (e) DC mining equipment;
- (f) Adjacent tanks, electrically connected and polarized to different potentials;
- (g) Unintentional connections to other structures or bonds to mitigate interference; and
- (h) DC welding equipment.

10.2.3 Comparison with Other Methods

10.2.3.1 Advantages

- (a) This method is especially useful for bare or ineffectively coated tanks; and
- (b) This method is advantageous in places where corrosion potentials may be low (for example, 500 mV or less negative) or the current required to meet a negative 850-mV polarized potential criterion would be considered excessive.

10.2.3.2 Disadvantages

- (a) Additional equipment is required;
- (b) Additional time may be required to set up equipment and to make tank-to-electrolyte potential measurements; and
- (c) Test results are difficult or impossible to analyze if foreign impressed current devices are present and cannot be interrupted or if stray currents are present.

10.2.4 Basic Test Equipment

10.2.4.1 A voltmeter with adequate input impedance. Commonly used digital instruments have a nominal impedance of 10 megohms. An analog instrument with an internal resistance of 100,000 ohms/volt may be adequate in certain circumstances in which the circuit resistance is low. A potentiometer circuit may be necessary in other instances.

10.2.4.1.1 Recording voltmeters can be useful for recording polarization decay.

10.2.4.2 Meter leads with insulated wire and terminal connections suitable for making reliable electrical contact with the tank and reference electrode. Color-coded meter leads are suggested to avoid confusion of polarity of the measured value.

10.2.4.3 Sufficient and adequate means to interrupt cathodic protection current sources such as sacrificial anodes, rectifiers, and electrical bonds that are influencing the tank simultaneously.

10.2.4.4 A CSE or other standard reference electrode may be used. Reference electrodes that may be substituted for the CSE are described in Paragraph 5.5.

10.2.5 The following procedure shall be used when this test is conducted:

10.2.5.1 Before the test, verify that cathodic protection equipment has been installed and is operating properly. Sufficient time should be allowed for the tank potentials to reach polarized values.

10.2.5.2 Provide means for current interruption in all DC current sources influencing the tank at the test site. The "off" interval should be kept as short as possible but still long enough to read a polarized tank-to-electrolyte potential after any "spike" (see Figure 2a) has collapsed.

10.2.5.3 Determine the location of reference electrode placement for potential measurements. Selection of a site may be based on:

- (a) Location accessible for future monitoring;
- (b) Other protection systems, structures, and anodes that may influence the structure-to-electrolyte potential;
- (c) Electrical midpoints between protective devices;
- (d) Known location of an ineffective coating if the tank structure is coated; and
- (e) Location of a known or suspected corrosive environment.

10.2.5.4 Make electrical contact between the reference electrode and the electrolyte at the test site in a location that minimizes the voltage gradient from other structures, and coating defects (if the tank is coated).

10.2.5.5 Record the location of the electrode to allow it to be returned to the same location for subsequent tests.

10.2.5.6 Connect the voltmeter to the tank and reference electrode as described in Paragraph 5.6.

10.2.5.6.1 If spiking could be present, use an appropriate instrument, such as an oscilloscope or high-speed recording device, to verify that the measured values are not influenced by a voltage spike.

10.2.5.7 Measure and record the tank-to-electrolyte "on" and instant-off potentials and their polarities with respect to the reference electrode.

10.2.5.7.1 The instant-off tank-to-electrolyte potential is the "baseline" potential from which the polarization decay is calculated.

10.2.5.8 Turn off the cathodic protection current sources that influence the tank (i.e., those interrupted in Paragraph 10.2.5.2) at the test site. Continue to measure and record the tank-to-electrolyte potential until it either:

- (a) Becomes at least 100 mV less negative than the instant-off potential, or
- (b) Reaches a stable depolarized level.

10.2.5.8.1 Measurements shall be made at sufficiently frequent intervals to avoid attaining and remaining at a corrosion potential for an unnecessarily extended period.

10.2.5.8.2 If extended polarization decay time periods are anticipated, it may be desirable to use recording voltmeters to determine when adequate polarization decay or a corrosion potential has been attained.

10.2.5.9 Record a sufficient number of measurements to determine the level of cathodic protection over the entire structure.

10.2.6 Evaluation of Data

10.2.6.1 Cathodic protection shall be judged adequate at the test site if 100 mV or more of polarization decay is measured with respect to a standard reference electrode.

10.2.7 Monitoring

10.2.7.1 When at least 100 mV or more of polarization decay has been measured, the tank "on" potential at the test site may be used for monitoring unless significant environmental, structural, coating integrity, or cathodic protection system parameters have changed.

10.3 Test Method 3b—Use of Tank Polarization Formation (Figure 2b)

10.3.1 This method provides a procedure using the formation of polarization to assess the adequacy of cathodic protection at a test site on a steel tank according to the criterion stated in NACE Standard RP0285:

"The following criterion shall apply: A minimum of 100 mV of cathodic polarization. The formation or decay of polarization can be measured to satisfy this criterion."

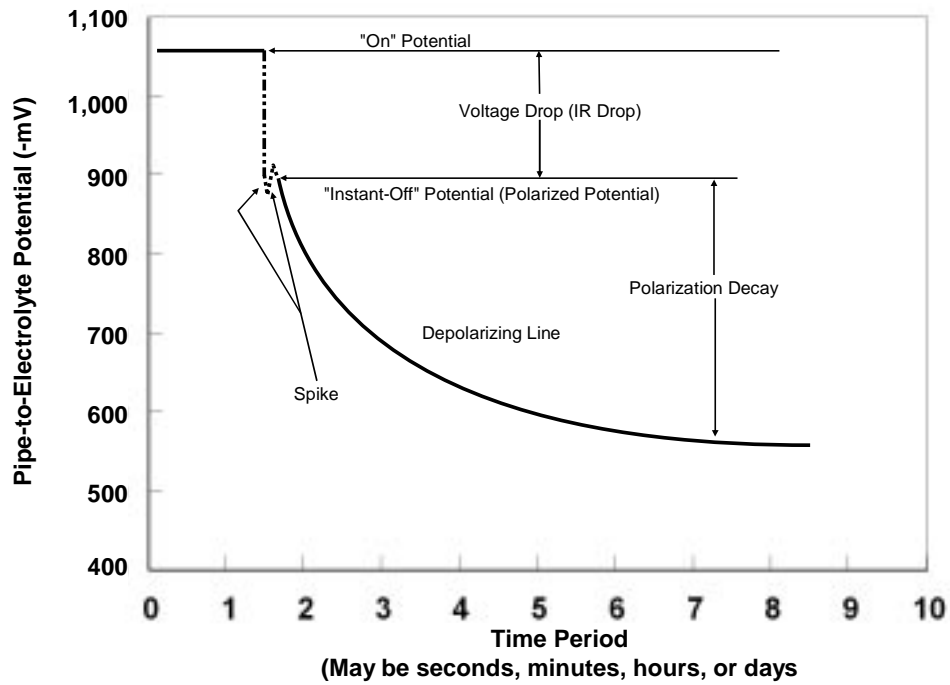


Figure 2a
Polarization Decay

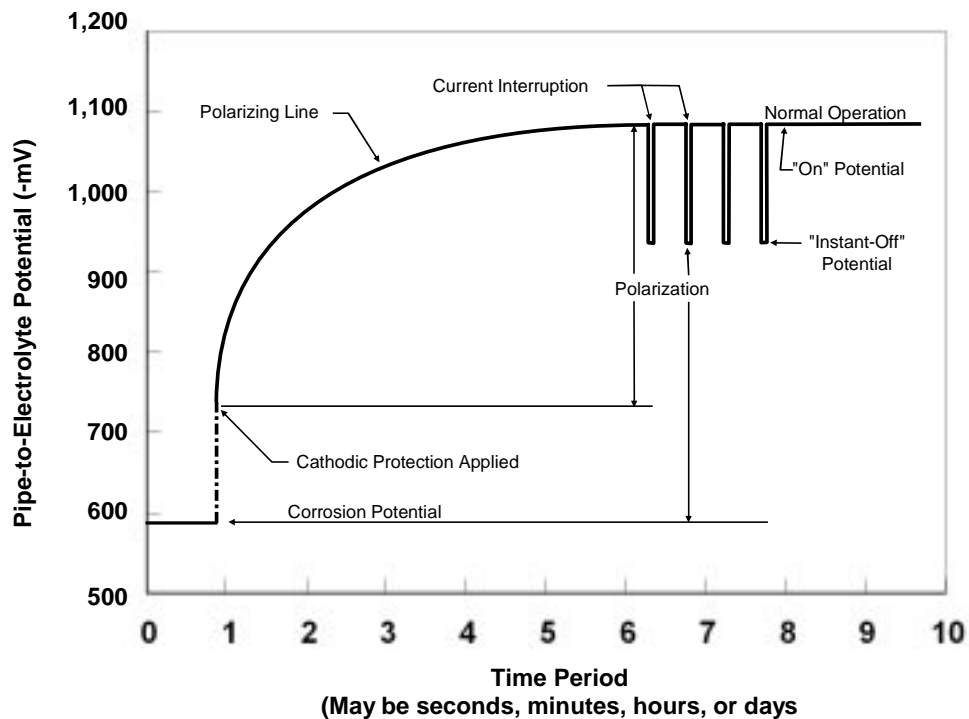


Figure 2b
Polarization Formation

FIGURE 2
Cathodic Polarization Curves

10.3.2 General

10.3.2.1 Steel tanks may be adequately protected if, from the "off" potential, applying cathodic protection causes a polarized potential that is at least 100 mV more negative.

10.3.2.2 Current sources that can affect the accuracy of this test method include the following:

- (a) Unknown, inaccessible, or direct-connected galvanic anodes;
- (b) Cathodic protection systems on associated tank systems or foreign structures;
- (c) Electric railway systems;
- (d) Galvanic, or bimetallic, cells;
- (e) DC mining equipment;
- (f) Adjacent tanks, electrically connected and polarized to different potentials;
- (g) Unintentional connections to other structures or bonds to mitigate interference; and
- (h) DC welding equipment.

10.3.3 Comparison with Other Methods

10.3.3.1 Advantages

- (a) This method is especially useful for a bare or ineffectively coated tank; and
- (b) This method is advantageous if corrosion potentials could be low (for example, 500 mV or less negative) or the current required to meet a negative 850-mV potential criterion would be considered excessive.

10.3.3.2 Disadvantages

- (a) Additional equipment is required;
- (b) Additional time may be required to set up equipment and to make the tank-to-electrolyte potential measurements; and
- (c) Test results are difficult or impossible to analyze if foreign impressed currents are present and cannot be interrupted or if stray currents are present.

10.3.4 Basic Test Equipment

10.3.4.1 A voltmeter with adequate input impedance. Commonly used digital instruments have a nominal impedance of 10 megohms. An analog instrument with an internal resistance of 100,000 ohms/volt may be adequate in certain circumstances in which the circuit resistance is low. A potentiometer circuit may be necessary in other instances.

10.3.4.2 Meter leads with insulated wire and terminal connections suitable for making reliable electrical contact with the tank and reference electrode. Color-coded meter leads are suggested

to avoid confusion of polarity of the measured value.

10.3.4.3 Sufficient and adequate means to interrupt cathodic protection current sources such as sacrificial anodes, rectifiers, and electrical bonds that are influencing the tank simultaneously.

10.3.4.4 A CSE or other standard reference electrode may be used. Reference electrodes that can be substituted for the CSE are described in Paragraph 5.5.

10.3.5 The following procedure shall be used when this test is conducted:

10.3.5.1 Before the test, verify that cathodic protection equipment has been installed but is not operating.

10.3.5.2 Determine the location of reference electrode placement for potential measurements. Selection of a site may be based on:

- (a) Location accessible for future monitoring;
- (b) Other protection systems, structures, and anodes that may influence the structure-to-electrolyte potential;
- (c) Electrical midpoints between protective devices;
- (d) Known location of an ineffective coating if the tank structure is coated; and
- (e) Location of a known or suspected corrosive environment.

10.3.5.3 Make electrical contact between the reference electrode and the electrolyte at the test site in a location that minimizes the voltage gradient from other structures, and coating defects (if the tank is coated).

10.3.5.4 Record the location of the electrode to allow it to be returned to the same location for subsequent tests.

10.3.5.5 Connect the voltmeter to the tank and reference electrode as described in Paragraph 5.6.

10.3.5.6 Measure and record the tank-to-electrolyte potential and its polarity with respect to the reference electrode.

10.3.5.6.1 This potential shall be the value from which the polarization formation is calculated.

10.3.5.7 Apply the cathodic protection current. Sufficient time should be allowed for the tank potentials to reach polarized values.

10.3.5.8 Install and place in operation necessary interrupter equipment in the DC current sources influencing the tank at the test site. The “off” interval should be kept as short as possible but still long enough to read a polarized tank-to-electrolyte potential after any “spike” (see Figure 2b) has collapsed.

10.3.5.9 Measure and record the tank-to-electrolyte “on” and instant-off potentials and their polarities with respect to the reference electrode. The difference between the instant-off potential and the original potential is the amount of polarization formation.

10.3.5.9.1 If spiking may be present, delay measurement of the tank-to-electrolyte potential to eliminate the spike voltages from the measured value. Spiking usually occurs within 0.5 second of the interruption of the cathodic protection currents. Appropriate instrumentation such as an oscilloscope or high-speed recording device may be used to

verify the presence and duration of the spiking.

10.3.5.10 Record a sufficient number of measurements to determine the level of cathodic protection over the entire structure.

10.3.6 Evaluation of Data

10.3.6.1 Cathodic protection shall be judged adequate if 100 mV or more of polarization formation is measured with respect to a standard reference electrode.

10.3.7 Monitoring

10.3.7.1 When at least 100 mV or more of polarization formation has been measured, the tank “on” potential may be used for monitoring unless significant environmental, structural, coating integrity, or cathodic protection system parameters have changed.

Section 11: Test Methods for Continuity Testing of Steel Tank Systems

11.1 The following test methods may be used to determine whether a tank is electrically continuous with piping, electrical equipment, conduit, and other appurtenances or structures in the immediate area. This list of tests is not all-inclusive. Other methods or equipment may be used to test for electrical continuity or discontinuity.

11.2 Underground storage tank (UST) systems may have been designed to be electrically isolated from other metallic structures such as piping, conduit, grounded electrical equipment, and hold-down devices. A lack of electrical isolation from these structures can result in lowered levels of cathodic protection or a reduction in the life of the cathodic protection system.

11.2.1 Some UST systems are designed to have electrical continuity between the tank and the related piping, electrical equipment, and other appurtenances or accessories. Discontinuity between the tank and another structure or appurtenance can result in a lack of protection, and in some cases, damage to the tank structure and/or appurtenances that are isolated.

11.3 Fixed Cell/Moving Ground Technique

11.3.1 This test method uses basic cathodic protection test equipment to test for an indication of possible electrical continuity through the use of structure-to-electrolyte potential comparison measurements.

11.3.2 The following procedure shall be followed when testing for continuity using the fixed cell/moving ground technique:

11.3.2.1 Make electrical contact between the reference electrode and the electrolyte at a location remote from the system to be tested.

11.3.2.1.1 The location should not be within the potential gradient of an anode or any other structure. Placement of the reference electrode in a location that is shielded by another tank or structure may result in erroneous data concerning the continuity of the shielded tank(s) or structures. Alternate reference electrode placements may be necessary to determine the continuity of all of the structures at a test site.

11.3.2.1.2 Once placed, the reference electrode shall not be moved for the duration of this test procedure.

11.3.2.2 Connect the voltmeter to the tank and reference electrode as described in Paragraph 5.6.

11.3.2.3 Measure and record the tank-to-electrolyte potential with respect to the reference electrode.

11.3.2.4 Disconnect the test lead from the tank and continue to test other structures by connecting that lead to the structure in question.

11.3.2.5 Measure and record structure-to-electrolyte potentials for structures that are to be evaluated.

11.3.3 Evaluation of Data

11.3.3.1 Electrical discontinuity is indicated for structures that have a potential difference greater than 0.01 V (10 mV).

11.3.3.2 Electrical continuity is indicated for structures that have a potential difference of 0.001 V (1 mV) or less.

11.3.3.3 The results of this test method are inconclusive and further testing is necessary if the measured potential difference of a structure is 0.01 to 0.001 V.

11.4 Potential Difference Technique

11.4.1 This technique is used to test for an indication of possible electrical continuity using a voltmeter to measure the difference in electrical potential between two buried structures.

11.4.2 To perform this test, one test lead from a voltmeter shall be connected to the structure to be tested. The second test lead from the voltmeter shall be connected to a separate structure or appurtenance that is suspected to be electrically continuous.

11.4.3 Evaluation of Data

11.4.3.1 Data obtained by this test method should be evaluated according to the same criteria used for the fixed cell/moving ground technique (Paragraph 11.3.3).

NOTE: Structures and appurtenances found on a UST system can misrepresent the results of this test. Galvanized pipe or conduit and coated or uncoated structures are some examples of different alloys or conditions that could be detrimental to the results of this test.

11.5 Applied Current Technique

11.5.1 This test uses either a temporary DC current source or an existing interruptible cathodic protection system and basic cathodic protection test equipment to determine electrical continuity. This test can also be used to confirm the fixed cell/moving ground and potential difference technique test results.

11.5.2 The following procedure shall be followed when testing using the applied current technique:

11.5.2.1 Make electrical contact between the reference electrode and the electrolyte at a location remote from the system to be tested.

11.5.2.1.1 The location should not be within the potential gradient of anodes or other structures. Placement of the reference electrode in a location that is shielded by another tank or structure may result in erroneous data concerning the continuity of the shielded tanks or structures. Alternate reference electrode placements may be necessary to determine the continuity of all structures at the test site.

11.5.2.1.2 Once placed, the reference electrode shall not be moved for the duration of this test procedure.

11.5.2.1.3 Prior to testing, existing impressed current cathodic protection systems should be turned off. If a sacrificial anode system is being used, the anodes should be disconnected from the structure, if practical.

11.5.2.2 Measure and record the tank-to-electrolyte potential with respect to the reference electrode.

11.5.2.3 Measure and record a structure-to-electrolyte potential for other structures under test.

11.5.2.4 Use either of the following for the applied current procedure:

- (a) Energize the existing impressed current cathodic protection system or sacrificial anode system; or
- (b) Energize a temporary groundbed. The temporary groundbed must be electrically isolated from the structures under test.

11.5.2.5 Remeasure and record the tank-to-electrolyte potentials with respect to the reference electrode.

11.5.2.6 Remeasure and record the structure-to-electrolyte potentials for structures that are designed to be continuous or isolated.

11.5.3 Evaluation of Data

11.5.3.1 The potentials taken before the CP system or groundbed was energized shall be compared with those taken afterward.

11.5.3.2 Structures that are electrically continuous with each other display similar negative shifts.

11.6 Invalid Techniques

11.6.1 Techniques utilizing "continuity testers" common to the electrical trades are not valid for continuity testing on underground storage tanks in a common electrolyte. Some equipment in this category includes the following:

- (a) DC ohmmeter
- (b) Diode tester
- (c) Continuity test light

11.7 Recommended Action

11.7.1 Further investigation may be required to confirm the presence or lack of continuity, depending on the original system design. For some systems, correction of the defect may preclude the installation of additional cathodic protection measures. In other instances, correction of the defect may be necessary in order for the original system or supplemental protection to be totally effective.

Section 12: Piping and Appurtenances

12.1 Cathodic protection for associated piping and appurtenances shall be tested in accordance with the

recommendations of NACE Standard RP0169³ and descriptions in NACE Publication 10A190.⁴

References

1. NACE Standard RP0285 (latest revision), "Corrosion Control of Underground Storage Tank Systems by Cathodic Protection" (Houston, TX: NACE).
2. NACE Standard RP0177 (latest revision), "Mitigation of Alternating Current and Lightning Effects on Metallic Structures and Corrosion Control Systems" (Houston, TX: NACE).
3. NACE Standard RP0169 (latest revision), "Control of External Corrosion on Underground or Submerged Metallic Piping Systems" (Houston, TX: NACE).

4. NACE Publication 10A190 (withdrawn), "Measurement Techniques Related to Criteria for Cathodic Protection of Underground or Submerged Steel Piping Systems (as defined in NACE Standard RP0169-83)" (Houston, TX: NACE).
5. NACE Publication 35201 (latest revision), "Technical Report on the Application and Interpretation of Data from External Coupons Used in the Evaluation of Cathodically Protected Metallic Structures" (Houston, TX: NACE).

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Appendix A: Using Coupons to Determine the Adequacy of Cathodic Protection

A.1 Coupons, particularly when accompanied by other engineering tools and data, have been used to evaluate whether cathodic protection at a test site complies with a given criterion.⁵

A.2 The small size of a coupon may reduce the effect of voltage drops due to currents from other sources. The magnitude of these voltage drops can be determined by interrupting cathodic protection current sources while the coupon is disconnected and noting whether there is a shift in the coupon-to-electrolyte potential.

A.3 These methods use coupons to assess the adequacy of cathodic protection applied to a selected test site. A cathodic protection coupon is a metal sample representing the tank at the test site and used for cathodic protection testing. The coupons used for these tests should be:

- (a) Of the same material and with the same or nearly the same properties as the tank;
- (b) Known not to interfere with determining the adequacy of the cathodic protection system;
- (c) On a coated tank, the size of the coupon should represent the largest anticipated coating defect;
- (d) Placed at tank depth in the same backfill as the tank;
- (e) Prepared with all mill scale and foreign materials removed from the surface; and
- (f) Placed at a location of an ineffective coating, if known.

A.4 During normal operations, a coupon has an insulated test lead brought above ground and connected to a tank test lead. The coupon receives cathodic protection current and represents the tank at the test site. For testing purposes, this connection is opened, and the polarized potential of the coupon is measured.

A.4.1 The time the connection is open to measure the coupon's instant-off potential should be minimized to avoid significant depolarization of the coupon. The coupon is then allowed to depolarize.

A.4.2 If possible, coupon current direction and magnitude should be verified using a current clip gauge or resistor permanently placed in series with the coupon lead. Measurements showing discharge of current from the coupon should be reason to question the validity of using a coupon at the test site.

A.5 The basic test equipment for both of these tests is the same:

A.5.1 Voltmeter with adequate input impedance. Commonly used digital instruments have a nominal impedance of 10 megohms. An analog instrument with an internal circuit resistance of 100,000 ohms/volt may be adequate in certain circumstances if the circuit

resistance is low. A potentiometer circuit may be necessary in other circumstances.

A.5.2 Meter leads with insulated wire and terminal connections suitable for making reliable electrical contact with the tank and reference electrode. Color-coded meter leads are suggested to avoid confusion of polarity of the measured value.

A.5.3 A CSE or other standard reference electrode may be used. Reference electrodes that may be substituted for the CSE are described in Paragraph 5.5.

A.6 Cathodic Protection Coupon Test Method A—for Negative 850-mV Polarized Tank-to-Electrolyte Potential of Steel Tank

A.6.1 This method uses a cathodic protection coupon to assess the adequacy of cathodic protection on a steel tank according to the criterion stated in NACE Standard RP0285:¹

“A negative polarized potential of at least 850 mV relative to a saturated copper/copper sulfate reference electrode.”

A.6.2 Comparison with Other Methods

A.6.2.1 Advantages

- (a) May provide a polarized coupon-to-electrolyte potential, free of voltage drop, with a minimum of specialized equipment, personnel, and vehicles; and
- (b) May provide a more comprehensive evaluation of the polarization at the test site than conventional tank-to-electrolyte potential measurements that may be influenced by the location, size, and number of coating holidays, if the tank is coated.

A.6.2.2 Disadvantages

- (a) May have high initial costs to install coupons, especially for existing tank.

A.6.3 Procedure

A.6.3.1 Before the test, verify that:

- (a) Cathodic protection equipment has been installed and is operating properly; and
- (b) Coupon is in place and connected to a tank test lead.

Sufficient time should be allowed for the tank and coupon potentials to reach polarized values.

A.6.3.2 Determine the location of coupon placement. Selection of a site may be based on:

- (a) Location accessible for future monitoring;
- (b) Other protection systems, structures, and anodes that may influence the tank-to-electrolyte and coupon-to-electrolyte potentials;
- (c) Electrical midpoints between protection devices;
- (d) Known location of an ineffective coating when the tank is coated; and
- (e) Location of a known or suspected corrosive environment.

A.6.3.3 Make electrical contact between the reference electrode and the electrolyte at the test site as close to the coupon as is practicable.

A.6.3.3.1 Record the location of the electrode to allow it to be returned to the same location for subsequent tests.

A.6.3.4 Connect the voltmeter to the coupon test lead and reference electrode as described in Paragraph 5.6.

A.6.3.5 Measure and record the tank and coupon "on" potentials.

A.6.3.6 Momentarily disconnect the coupon test lead from the tank test lead and immediately measure and record the coupon-to-electrolyte instant-off potential and its polarity with respect to the reference electrode. This should be performed quickly to avoid depolarization of the coupon.

A.6.3.7 Reconnect the coupon test lead to the tank test lead for normal operations.

A.6.4 Evaluation of Data

A.6.4.1 Cathodic protection may be judged adequate at the test site if the polarized coupon-to-electrolyte potential is negative 850 mV, or more negative, with respect to a CSE.

A.6.4.2 The polarized potential of the coupon depends on the coupon surface condition, the soil in which the coupon is placed, its level of polarization, and the amount of time it has been polarized. Therefore, the polarized potential of the coupon may not be the same as that of the tank and may not accurately reflect the polarization on the tank at the coupon location.

A.6.4.3 The polarization measured on the tank is a "resultant" of the variations of polarization on the tank at the test site. The causes of these variations include the tank surface condition, soil

strata variations, oxygen differentials, and length of time the tank has been polarized. Making precise comparisons between the polarization of the tank and the polarization of the coupon may not be possible.

A.6.5 Monitoring

A.6.5.1 When the polarized coupon-to-electrolyte potential has been determined to equal or to exceed a negative 850 mV, the tank "on" potential may be used for monitoring unless significant environmental, structural, coating integrity, or cathodic protection system parameters have changed.

A.7 Cathodic Protection Coupon Test Method B—for 100-mV Cathodic Polarization of a Steel Tank

A.7.1 This method uses cathodic protection coupon polarization decay to assess the adequacy of cathodic protection on a steel tank according to the criterion stated in NACE Standard RP0285,¹ as follows:

"The following criterion shall apply: A minimum of 100 mV of cathodic polarization between the structure surface and a stable reference electrode contacting the electrolyte. The formation or decay of polarization can be measured to satisfy this criterion."

A.7.2 Comparison with Other Methods

A.7.2.1 Advantages

- (a) Can measure coupon-to-electrolyte polarization formation or decay with a minimum of specialized equipment, personnel, and vehicles; and
- (b) Can provide an indication of the amount of polarization present at the test site without interrupting the cathodic protection current supplied to the tank.

A.7.2.2 Disadvantages

- (a) Initial installation of coupons can be expensive, especially for an existing tank.

A.7.3 Procedure

A.7.3.1 Before the test, verify that:

- (a) Cathodic protection equipment is installed and operating properly; and
- (b) Coupon is in place and connected to a tank test lead.

Sufficient time shall be allowed for the tank and coupon potentials to reach polarized values.

A.7.3.2 Determine the location of coupon placement for potential measurements. Selection of a site may be based on:

- (a) Location accessible for future monitoring;
- (b) Other protection systems, structures, and anodes that may influence the tank-to-electrolyte and coupon-to-electrolyte potentials;
- (c) Electrical midpoints between protection devices;
- (d) Known location of an ineffective coating if the tank is coated; and
- (e) Location of a known or suspected corrosive environment.

A.7.3.3 Make electrical contact between the reference electrode and the electrolyte at the test site as close to the coupon as is practicable.

A.7.3.3.1 Record the location of the electrode to allow it to be returned to the same location for subsequent tests.

A.7.3.4 Connect the voltmeter to the coupon test lead and reference electrode as described in Paragraph 5.6.

A.7.3.5 Measure and record the tank and coupon "on" potentials.

A.7.3.6 Disconnect the coupon test lead from the tank test lead and immediately measure the coupon-to-electrolyte potential.

A.7.3.6.1 The coupon-to-electrolyte potential becomes the "base line value" from which polarization decay is measured.

A.7.3.7 Record the coupon-to-electrolyte instant-off potential and its polarity with respect to the reference electrode.

A.7.3.8 Leave the coupon test lead disconnected to allow the coupon to depolarize.

A.7.3.9 Measure and record the coupon-to-electrolyte potential periodically. The difference between it and the instant-off potential is the amount of polarization decay. Continue to measure and record the coupon-to-electrolyte potential until it either:

- (a) Has become at least 100 mV less negative than the instant-off potential; or
- (b) Has reached a stable depolarized level.

A.7.3.10 Reconnect the coupon test lead to the tank test lead for normal operations.

A.7.3.11 The use of polarization formation, as stated in the criterion, can also be used to assess the adequacy of cathodic protection. The procedure is different in that a "base line value" for the coupon is measured prior to connection to the tank. That potential is then compared to the instant-off potential of the coupon after it has been allowed to polarize.

A.7.4 Evaluation of Data

A.7.4.1 Cathodic protection may be judged adequate at the test site if 100 mV or more of polarization formation or decay is measured with respect to a standard reference electrode.

A.7.4.2 The depolarized potential of the coupon depends on the coupon surface condition, the soil in which the coupon is placed, its level of polarization, and its time polarized. Therefore, the depolarized potential of the coupon may not be the same as that of the tank and may not accurately reflect the polarization on the tank at the coupon location.

A.7.4.3 The polarization measured on the tank is a "resultant" of the variations of polarization on the tank at the test site. These variations are caused by the tank surface condition, soil strata variations, oxygen differentials, and time the tank has been polarized. Making precise comparisons between the polarization of the tank and the polarization of the coupon may not be possible.

A.7.5 Monitoring

A.7.5.1 When at least 100 mV or more of polarization formation or decay has been measured, the tank "on" potential at the test site may be used for monitoring unless significant environmental, structural, coating integrity, or cathodic protection system parameters have changed.

TM0101-2001

ISBN 1-57590-137-4
NACE International